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DEPARTMENT OF TELECOMMUNICATIONS

Master Thesis Report

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To my parents and sister.

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“*Those things which I am saying now may be obscure, yet they will be made clearer in their proper place.*”

Mikołaj Kopernik (Poland, 1473-1543)

Abstract

There is no doubt that positioning systems has been one of the greatest improvements in technology in the last quarter of the 20th century. Knowing the position of any object everywhere in the world by calculations of the signals received by the satellites has revolutionized different areas. What began as a military advances race between the U.S.A. and the U.R.S.S. during the Cold War, nowadays it seems to belong to the civil users instead to their developers. It is so much so, that in recent years these systems have been modified to be opened to the civil users, even proliferating new non-military systems.

This Thesis is divided in three parts. The first part includes an introduction about positioning and there is an examination of the different current positioning systems, as well as the systems that are being developed. Due to their significance, GPS, GLONASS and Galileo are described widely than the rest. Even though, the main objective of this Thesis is the GPS.

In the second part, there is an examination of the error sources that affect the accuracy in GPS positioning, to explain which of them can be corrected and how. Moreover, one can find a description of the techniques to improve accuracy used in GPS, called Augmentation Systems, with special mention to SBAS and AGPS. This last one, very popular nowadays thanks to the *Smartphone's*.

By last, there is an introduction about *Tracking Systems*, one of the most benefited by the positioning systems, in which is analyzed the different existing systems. Furthermore, a short description about a selection of significant products in the market is done. With this, the reader can get a global idea about the *Tracking Systems* and their possible applications.

No cabe duda que los sistemas de posicionamiento han sido uno de los grandes avances en tecnología del último cuarto del siglo XX. El hecho de poder conocer la posición de un objeto mediante cálculos realizados por señales enviadas por satétiles y con cobertura global, ha supuesto una revolución en distintas áreas. Lo que comenzó como una carrera de avances militares entre los EE. UU. y la U.R.S.S. en plena Guerra Fría, ahora parece pertenecer más a los usuarios civiles que a los militares. Tanto es así que en los últimos años, esos sistemas se están abriendo más y más a los usuarios civiles, e incluso están proliferando otros sin fines militares.

Esta Tesis está dividida en tres partes. En la primera parte se introduce el concepto de posicionamiento y se estudian los sistemas de posicionamiento que actualmente existen así como los que están en proceso de desarrollo. Debido a su importancia, se explican con mayor detalle los sistemas GPS, GLONASS y Galileo. Aún así el objetivo de esta tesis es el sistema GPS.

En la segunda parte, se examinan las fuentes de error que afectan la precisión en el posicionamiento del sistema GPS, para ver cuáles de ellas pueden ser corregidas y cómo hacerlo. Con esto, se describen las técnicas existentes en GPS para mejorar la precisión, con carácter especial para los SBAS y AGPS. Éste último, en auge con la aparición de los smartphones.

Por último, se introducen los Tracking Systems, *uno de los grandes beneficiados por los sistemas de posicionamiento. Se analizan los diferentes sistemas existentes y se hace un pequeño estudio sobre una selección de los productos que el usuario puede encontrar en el mercado. Con esto, se pretende ofrecer al lector un idea global sobre los* Tracking Systems *y de sus posibles aplicaciones.*

Contents

List of Figures

List of Tables

Part I

Positioning Systems

Chapter 1

Introduction

In this chapter are presented the basic principles in positioning, from the most primitive methods until the positioning using artificial satellites. There is also a comparison between how the lighthouses and the satellites work, in order to give the reader an easier idea about the principle of working of the satellite based positioning systems.

1.1 Basic principles in positioning

Since the beginning of history humans have had the need to position themselves in the environment. Identify and remember objects and marks as reference points were the techniques that primitive man used to find the path through jungles and deserts. Leaving stones, marking trees or referencing mountains, were the first aids to navigation, and therefore the first *benchmarks*.

Making a leap in time, one can see how the man comes a time when feels the need to "conquer" the ocean. This is when the reference systems used for the immediate environment are obsolete and the needs to resort to other techniques such as astronomy. When you set out to explore the oceans, where the only visible objects are the sun, moon and stars, they began to be points of reference and then began the era of celestial navigation.

The relative position of the stars and their geometric arrangement look different from different places of the earth. Therefore, observing the configuration of the stars one could estimate its position on earth and the direction it should take to its destination. To improve accuracy, were invented special optical instruments for measuring angles of view between the stars. These angles were then used to determine the position of the observer with the help of precomputed charts that facilitated the tedium of manual calculations.

Later, with the arrival of radio signals, it was possible to locate moving objects through static items in the land distributed by man. The system is easy to explain using an example based on an even more primitive, the positioning of ships through fog. In addition, this example also can be extrapolated to the system based on GPS positioning, which focused this study.

The basic observable of the GPS system is the time of propagation of the electromagnetic wave between the satellite (transmitter) and the receiver. This time, multiplied by the speed of light, gives us a measure of the distance (pseudorange) between them.

To explain the principles of working of the GPS, a basic example of positioning a boat near the coast will be explained. Let's suppose that a lighthouse with known coordinates, emitting acoustic signals periodically. Suppose also a boat with a perfectly synchronised clock to the lighthouse's clock receiving the signal just 30 seconds after the time the lighthouse is emitting the signal. These 30 seconds will correspond to the propagation time the sound spends in arriving from the lighthouse (transmitter) to the boat (receiver). Taking into account that the propagation time of the sound in the air is about 335 m/s, it is easy to calculate the distance between both objects.

$$d = 335m/s \cdot 30s = 10,050m = 10.05km$$

Due to the nature of the sound (let's suppose that the source is omnidirectional), the boat will be placed over a point of the circle with radius d described by the transmitter source (see Figure 1.1). If now another lighthouse is added, the boat will receive two different signal, one from every transmitter, so the whole circle will be reduced to only the intersection points of both circles. In addition, with a third lighthouse, the ambiguity of the position explained before is solved (see Figure 1.1).

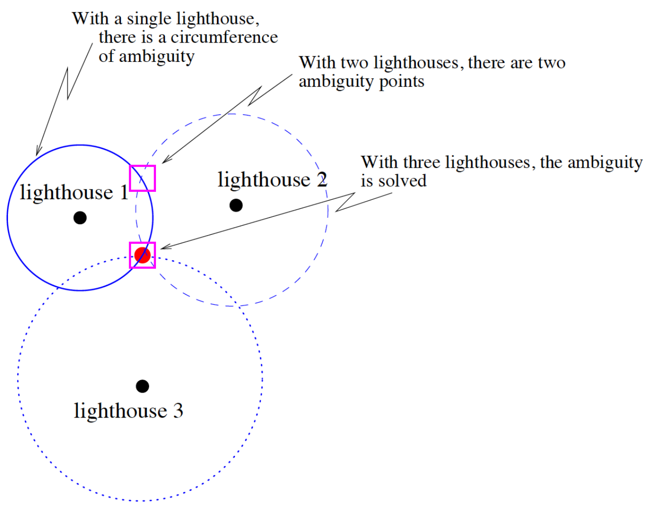


Figure 1.1: 2D Positioning [1]

The preceding example states the basic principle of working of GPS. Considering the space of GPS as 3 dimensions, another “lighthouse” is needed in order to solve the ambiguity.

Summarising the example, these are the highlights from one system to the other [1]:

- In the case of the lighthouses, one assumes that their coordinates are known. In the case of the GPS satellites, these are calculated from the transmitted ephemerides.

- In the GPS positioning, as well as in the example, distances between receiver and satellites are calculated using the propagation time of a signal (in this case, an electromagnetic wave) from the satellite to the receiver.

In the above example is not taken into consideration the error in the synchronism of clocks between the transmitter stations and the receiver. Obviously, a perfect synchronism is impossible when is put into practice, thus a region of uncertainty appears at the intersection of the circles.

As shown in Figure 1.2, the intersection between the circles generates an area in which the receiver can be found, the greater the desynchronism between clocks, the greater the area of uncertainty.

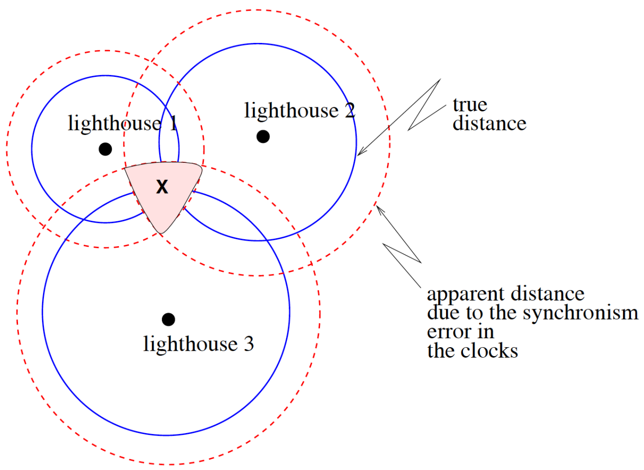


Figure 1.2: Clock error effect in positioning [1]

Moreover, the size of the area not only depends on the synchronism error but the source position with respect to the receiver transmitter. Figure 1.3 exemplifies this case, called Dilution of Precision (DOP[1]).

[1]DOP is the statistical relationship between the average range domain error and the position error [15]

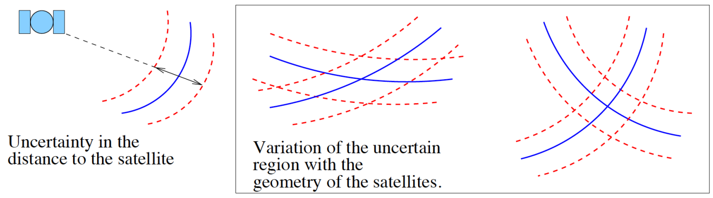


Figure 1.3: Dilution of Precision effect [1]

In order to minimize synchronism errors, GPS satellites have highly accurate atomic clocks with stabilities of about 10^{-13}. Commercial receivers, however, use quartz clocks much more unstable but less expensive. The way to combat the ambiguity for the end user is to predict the error of synchronism when the coordinates are calculated.

Chapter 2

GPS, GLONASS, GALILEO and other Positioning Systems

2.1 Global Positioning System (GPS)

Positioning systems has been one of the greatest improvements in technology in the last quarter of the 20th century. Knowing the position of any object everywhere in the world by calculations of the signals received by the satellites has revolutionized different areas. What began as a military advances race between the U.S.A. and the U.R.S.S. during the Cold War, nowadays it seems to belong to the civil users instead to their developers. It is so much so, that in recent years these systems have been modified to be opened to the civil users, even proliferating new non-military systems. This part of the Thesis includes an introduction about positioning and there is an examination of the different current positioning systems, as well as the systems that are being developed. Due to their significance, GPS, GLONASS and Galileo are described widely than the rest, even though, the reader can get a global idea about each and every one of the systems.

2.1.1 Principles of working

The NAVSTAR-GPS [22] (NAVigation System with Time And Ranging Global Positioning System) or commonly named GPS (Global Positioning System) is a Global Navigation Satellite System (GNSS) that determines in every part of the world the position of an object, a person, vehicle or vessel, with accuracy up to centimetre depending on the technology used, although is usual a few meters of accuracy [2]. The operational GPS satellites are nominally maintained within 24 orbital slots. These slots reside within circular orbits inclined 55º with respect to the equatorial plane. Four slots are contained in each of six orbital planes, with an orbital radius of 26,559.7 km. In order to determine the position, the receiver automatically locate at least three satellites[1] in the network, from which receives a signal indicating identification and clock hour of every of them [23]. Once the receiver has gathered all that signals, the device synchronizes the GPS clock and calculates the time it takes to get the signals from the satellites to the antenna, and thereby measure the distance to the satellite using trilateration[2], which is based to determine the distance of each satellite relative to the point of measurement. With the known distance, the determination of the relative position of the object to the three satellites is instantaneous. Therefore, knowing well the coordinates or position of each of the signal emitted by the satellites, the receiver can obtain the absolute position or actual coordinates of the measurement.

The GPS is formed by three segments (see Figure 2.1) :

- Space Segment (SS)
- Control Segment (CS)
- User segment (US)

[1]The location with three satellites determines 2 points in the interesection of the three spheres. In the case that the object is on the earth surface, one of these points could be discarded. If the object is in the air (i.e. an airplane) there will be ambiguity between both points, so another satellite will be needed at least to determine a unique position.

[2]Trilateration using GPS is to find the distance of each of the three signals to the point of measurement. Knowing the three distances, the pseudorange is easily determined by one's position relative to the three satellites. It is also essential to know the coordinates or position of each satellite. In this way we obtain the absolute position or actual coordinates of the measurement.

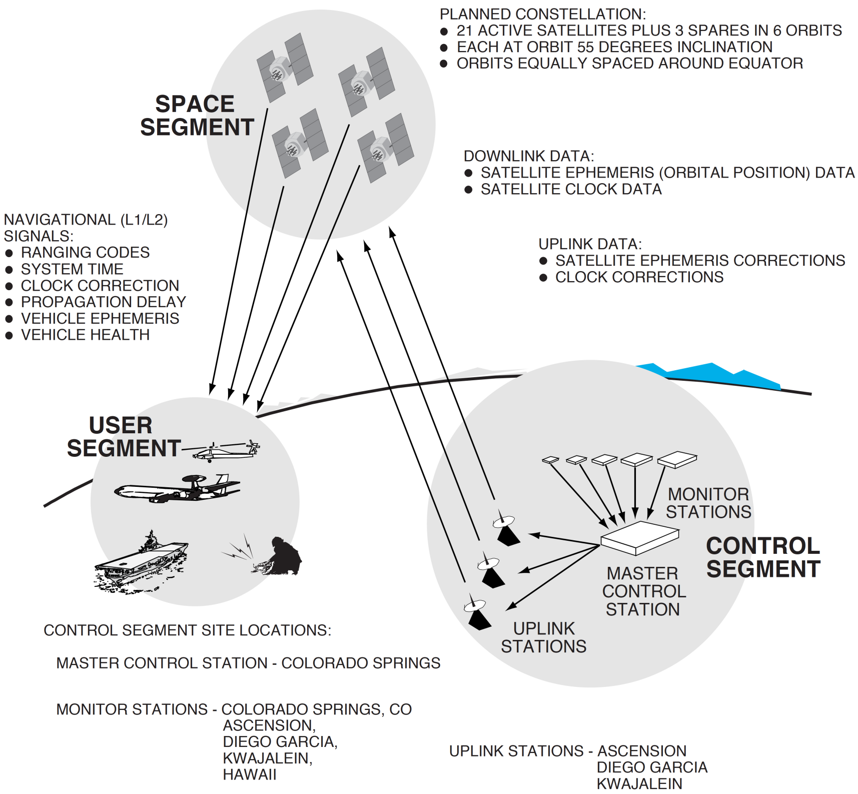


Figure 2.1: GPS Segments [2]

2.1.1.1 Space Segment

The main functions of this segment are, from the instructions received by the control segment, to provide an atomic clock reference signal, to generate the pseudorandom Radiofrequency (RF) signals and to save and forward the navigation message. In order to carry out that functions, the space segment is formed by:

- The constellation
- The Satellites
- The GPS signal

The constellation

The space segment is nominally formed by a 24 satellite constellation (see Table 2.1), distributed in 6 orbital planes with an inclination of 55º with respect to the equatorial plane. The orbits of the satellites are almost circular, their eccentricity is less than 0.02, with an orbital radius of 26,559.7km and a period of 12 sidereus hours (11h 58min. 2sec.). This configuration was designed so that at any point on the earth always had a minimum of 4 satellites visible above the horizon of the observer, with an elevation angle above 15 degrees.

Table 2.1: Nominal GPS Constellation Slot Locations

Slot	Right Ascension of the Ascending Node (º)	Argument of Latitude (º)
A1	272.847	268.126
A2	272.847	161.786
A3	272.847	11.676
A4	272.847	41.806
B1	332.847	80.956
B2	332.847	173.336
B3	332.847	309.976
B4	332.847	204.376
C1	32.847	111.876
C2	32.847	11.796
C3	32.847	339.666
C4	32.847	241.556
D1	92.847	135.226
D2	92.847	265.446
D3	92.847	35.156
D4	92.847	167.356
E1	152.847	197.046
E2	152.847	302.596
E3	152.847	66.066
E4	152.847	333.686
F1	212.847	238.886
F2	212.847	345.226
F3	212.847	105.206
F4	212.847	135.346

In order to provide robustness in performance against satellite failures, the constellation design includes asymmetrical spacing in argument of latitude between satellites within each plane. With this, when a new satellite is launched, it is placed near one of the slots that contain a satellite expected to require replacement in a short period of time. Since the first satellite launched on 1978 there has been 62 launches, although the current constellation is formed by 31 satellites (see Figure 2.2) [24].

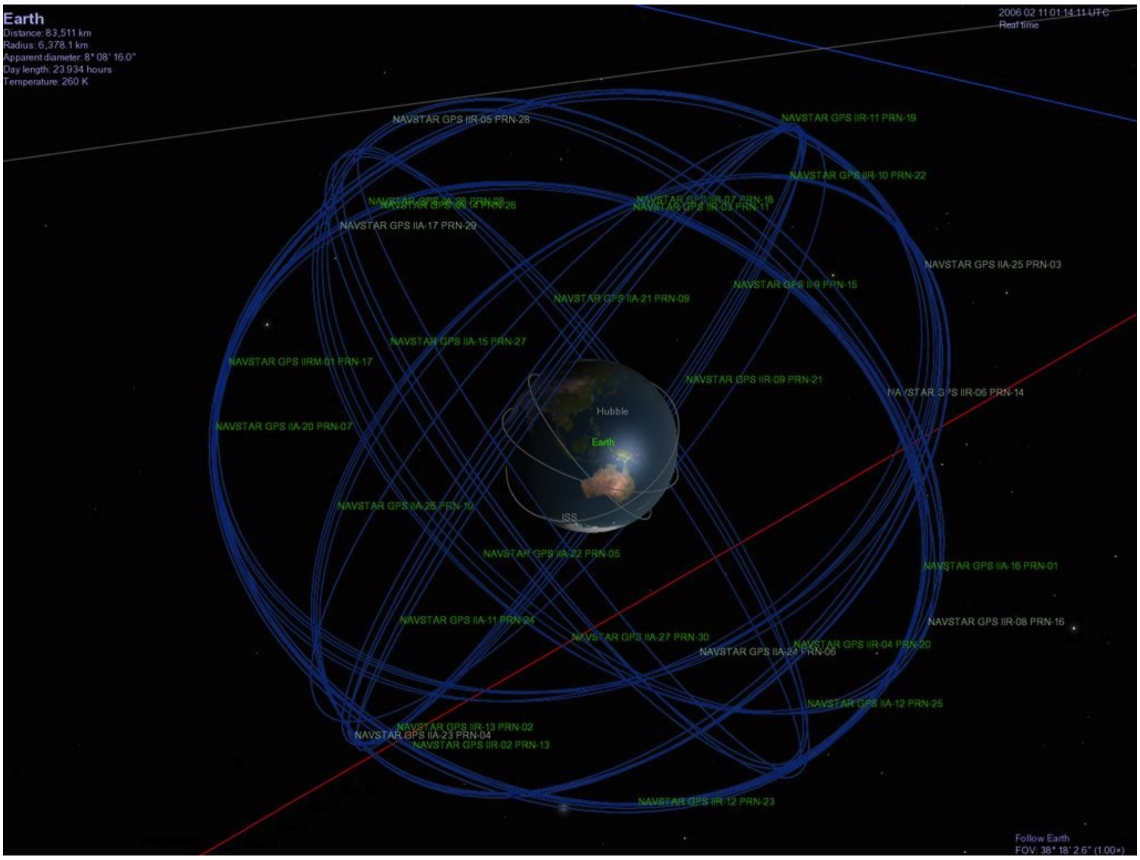


Figure 2.2: GPS Constellation [3]

The Kleperian elements needed by the satellites to be properly positioned in the constellation are (see Figure 2.3) [1]:

[Ω] Right ascension of ascending node is the geocentric angle between the ascending node direction and the Aries point. The node line is the intersection with the equatorial plane and the orbital plane. Its intersection with the unit sphere defines two points: the ascending node, through which the satellite crosses to the region of positive Z, and the descending one.

[i] Inclination of orbital plane is the angle between the orbital plane and equator.

[ω] Argument of perigee is the angle between node directions and perigee, measured in the orbital plane. The perigee is the point of closest approach of the satellite with respect to the centre of mass of the Earth. The most distant position is the apogee. Both are in the semi-major axis direction.

[a] **Semi-major axis of orbital ellipse** is the semi-major axis of the ellipse defining the orbit.

[e] **Numerical eccentricity of the orbit** is the eccentricity of the orbital ellipse.

[T_0] **Perigee passing time** is the time of the satellite passage through the closest approach with the Earth (perigee). Satellite orbital position can be obtained at a moment t using $\tau(t) = t - T_0$ or any of the three following anomalies:

[$v\,(t)$] **True anomaly** is the geocentric angle between perigee direction and satellite direction.

[$E\,(t)$] **Eccentric anomaly** is the angle, measured from the centre of the orbit, between the perigee and the direction of the intersection point of the normal line to the major axis passing through the satellite with the circle of radius a.

[$M\,(t)$] **Mean anomaly** is a mathematical abstraction.

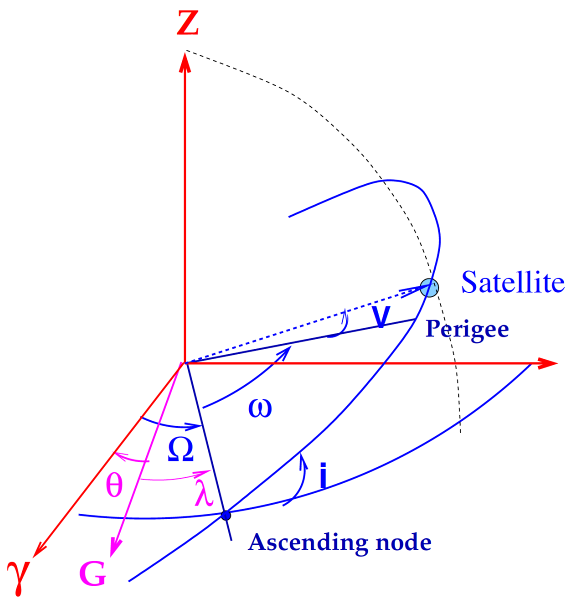


Figure 2.3: Orbital parameters [1]

The satellites

The space vehicles (SVs) have structures and mechanisms to maintain the correct orbit, communicate with the control segment and transmit the signals to the receivers. The most critical point in the SVs is the synchronism in their clocks, as a result, all the satellites are equipped with atomic clocks (Rubidium (Rb) or Cesium (Cs)) which provide very high stability.

Each GPS satellite is identified in several ways: regarding its position in the orbital plane, every satellite is placed in a slot (1, 2, 3...) inside of the 6 orbits (A, B, C, D, E or F); by the NASA cataloging number; by the international identification number, by the PRN Code (Pseudorandom Noise code); and by the sequence launch number or Space Vehicles Number (SVN).

During the GPS life, there have been developed some satellite groups [2]:

- *Block I:*

  The Block I Space Vehicles, built by Rockwell International as developmental prototypes, were launched between 1978 and 1985 from VAFB, CA. These SVs supported most of the system testing. The Air Force launched the first Block I research and development satellite in February 1978, and as of February 1991, the GPS network consisted of six Block I R&D satellites. These satellites were used for the development and testing of Navstar receivers and user equipment and they were not equipped with the Selective Availability (S/A). The average life was around 4.5 years, although some of the last SVs launched worked during 10 years. These SVs were able to provide service to the users without the necessity of communicate with the Control Segment for 3-4 days.

- *Block II/IIA:*

  Some of these SVs are currently operating. The first SVs launched were called Block II, but since 1990 there were improvements in them and the block was called Block IIA (Advanced) enabling the mutual communication between SVs. 9 Block II satellites were launched between 1986 and 1990; 19 Block IIA versions were launched between 1990 and 1997.

  Enhancements consisted in harden the electronics to radiation to prevent random memory upset events to improve SIS reliability and survivability [25]. These new SVs had the capacity to store 180 days of navigation message data to guarantee SIS[3] availability. In order to provide SIS security, there were implemented the Selective Availability (S/A) and Anti-Spoof (AS), which will be described later (See 2.1.1.1). To maximize SIS integrity and protect user from tracking a faulty SV, the satellites are capable to automatically detect certain error conditions and switch to non-standard PRN Code transmission or default navigation message data.

[3]SIS: Signal-in-Space

- *Block IIR Operational Replacement Satellites:*

  These SVs were made to replace the Block IIA satellites and the improvements were the ability to determine its orbit and generate navigation message data itself. Block IIR SVs are able to measure distances between SVs and transmit observations to other SVs or to the Control Segment. Thanks to these enhancements, SVs can operate up to half a year without control segment support with a non-degradation of the accuracy in ephemerides. 13 SVs have been launched with currently 12 of them active due to the launch failure of the first satellite on January of 1997. The last launch was on June of 2006.

- *Block IIR-M:*

  The IIR-M capabilities include developmental military-use-only M-code on the L1 and L2 signals and a civil code on the L2 signal. There are eight satellites in the Block IIR-M series, which were built by Lockheed Martin. The first Block IIR-M satellite was launched on September 26, 2005. The final launch of a IIR-M was on August 17, 2009 with a total of 8 SVs currently working.

- *Block IIF, Follow-On Operation Satellites:*

  The first launch of a Block IIF SV was on May the 27th of 2010 [26] and from August the 27th is correctly working [27]. These satellites are functionally equivalent to the IIR/IIR-M SVs and pave the way towards operational M-code after IOT&E in 2010. Block IIF satellites also add a new separate signal for civilian use, designed L5 (1,176.45 MHz.). The improvements also include an on-board reprogrammable processor, which will continue to deploy the modernization efforts of the IIR-M satellites, a 12-year design life, and a more robust military signal. Figure 2.4 [28] shows a representation of three different satellites, the first one corresponding to the Block I, in the middle one IIA satellite and on the right the latest Block IIF satellite launched.

Figure 2.4: Evolution of the GPS satellites [4]

- *Block III:*

  The GPS Block III is an initiative of the US Air Force intended to meet the requirements for satellite-based navigation and timing capabilities over the next 30 years. Two industry teams led by Lockheed-Martin and Boeing are currently competing for the GPS Block III program. Finally, the US Air Force selected Lockheed-Martin [29] led team to build eight (up to 12) GPS IIIA satellites worth \$1.4 billion with the first spacecraft to be placed into orbit in 2014. The US Air Force GPS Block III plans call for the procurement of eight GPS IIIB and 16 GPS IIIC satellites in later increments.

  The GPS IIIA satellites will deliver significant improvements over current GPS space vehicles, including a new international civil signal (L1C) and increased M-Code anti-jam power with full earth coverage for military users. GPS IIIB will enable a cross-linked command and control architecture, allowing these GPS III vehicles to be updated from a single ground station instead of waiting for each satellite to orbit in view of a ground antenna. GPS IIIC will include a high-powered spot beam to deliver greater M-Code power for increased resistance to hostile jamming [30, 31].

The signals

Since the Block I was launched, the SVs have been incorporating a number of improvements to the signals. Even today, the received message from the latest satellites sent into space is not in its fullness like the signals that are planned to be transmitted in the future (when the Block III will be fully operational). That is the main reason for, to understand the operation of GPS receivers to calculate their position on earth, an insight into the evolution of these signals for over 30 years since the GPS system in operation should be done. Since the very beginning of GPS there have been using two different frequencies to transmit different types of messages. Each improvement in the satellite blocks, previously described (see 2.1.1.1), has led to an improvement in the transmitted signal, either in the alteration of any part of the plot, as in the introduction of new messages or transmission bands.

The transmitted signals by Block I, remain the basis of communication between the satellites and the GPS receiver. Other signals have been developed in order to improve positioning accuracy, either civilian or military user-level.

In this part, it is going to be explained the frequencies and bands used by the most significant satellite blocks. Later, the survey will be focused on the procedure of acquiring the position by the signals received.

- *From Block I to IIR:*

  From Block I to Block IIR, two frequencies were designed to transmit the necessary information from the satellites to the GPS receiver. The frequencies correspond to L1 and L2, 1,575.42 MHz and 1,227.6 MHz respectively. These frequencies are related with the atomic oscillator used to generate since are multiples of the fundamental frequency. For that, only one atomic clock should be needed (theoretically) to get two precise carriers [1].

$$L1 = 154{\cdot}10.23\text{MHz}{=}1575.42\text{MHz}$$
$$L2 = 120{\cdot}10.23\text{MHz}{=}1227.60\text{MHz}$$

  Due to all the satellites broadcast the message over the same frequencies, CDMA (Code Division Multiple Access) is used in order to avoid interferences between them.

  There are two types of services provided by GPS, SPS (Standard Positioning System) and PPS (Precision Positioning System) based on who the end user. Due to the fact the GPS system was invented by the U.S. military, the PPS service is encrypted for only military use and authorized civilian users, while the SPS service may be used freely but its accuracy is not as good as the military.

Over the L1 carrier (1,575.42 MHz), two Direct-Sequence Spread-Spectrum (DSSS) with rectangular symbols Signals are broadcast in phase quadrature [2]. These signals are:

- *Coarse Acquisition [C/A]:* it is also known as civilian code. This sequence is repeated every millisecond and at a velocity, or "chip-rate", of 1 Mbps, which is equivalent to a wavelength of 293.1 m The C/A code is generated using length-1023 Gold codes, which repeat every millisecond. The signal can be jammed by provider in war conditions in determinate areas such as over a battlefield in order to prevent the security of the U.S. Army.
- *Precision code [P(t)]*: it is reserved for military use and authorized civilian users. The sequence is repeated every 266 days (38 weeks) and a weekly portion of this code is assigned to every satellite, called PRN sequence. Its velocity (or "chip-rate") is 10 Mbps, equivalent to a wavelength of 29.31 m If it is encrypted, the Precision code is called P(Y).

Both the C/A and P(Y) code signals are further modulated by the same 50 bps data. This 50 bps data stream includes information required for navigation including the ephemeris, clock corrections, and health information for the broadcasting satellite, as well as almanac data for the entire constellation. This message is called Navigation Message ($D\left(t\right)$). About the L2 carrier (1,227.6 MHz), only the P(Y) message is broadcasted on. As a consequence, it is possible to correct the errors due to the ionospheric refraction because the signal is broadcasted in two different frequencies.

The structure of the satellite modulator is shown in Figure 2.5.

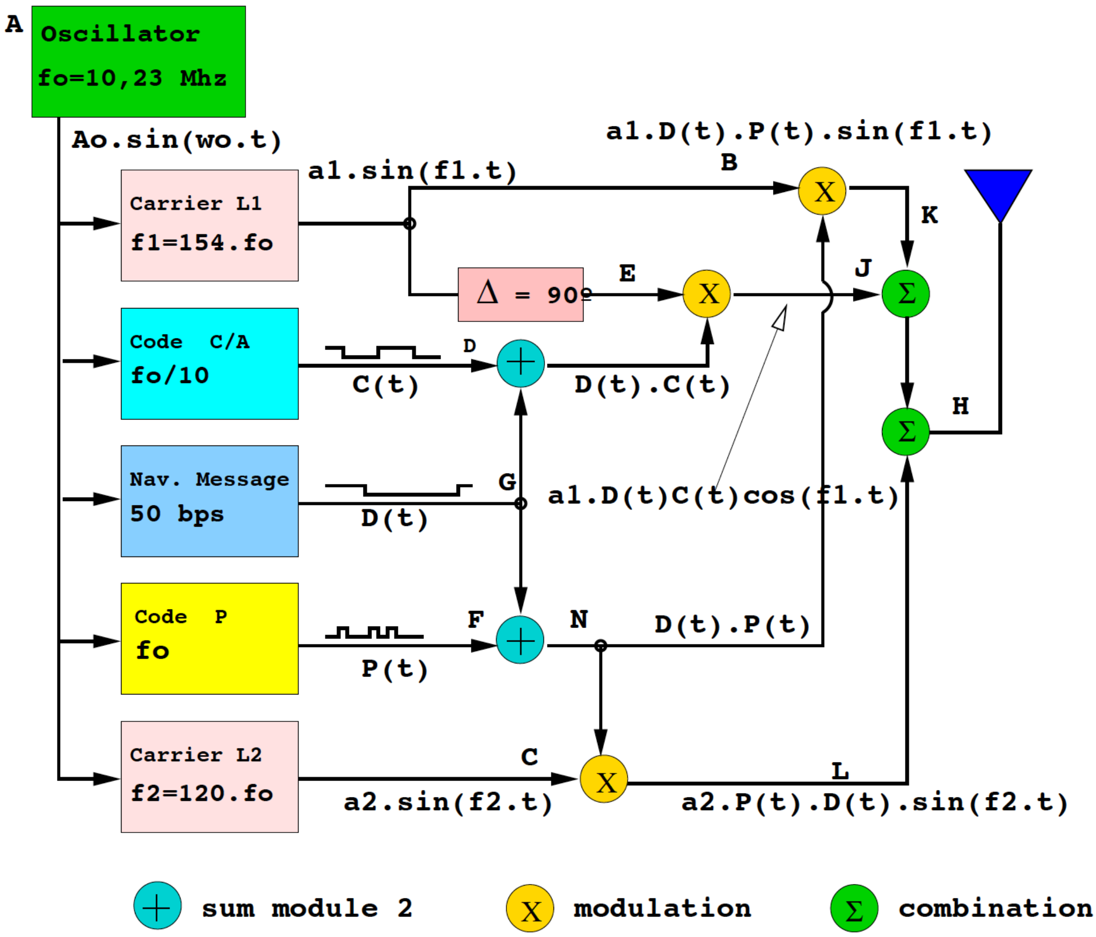


Figure 2.5: GPS signal structure [1]

Mathematically, both carriers could be expressed as:

$$
\begin{aligned}
L1(t) &= a_1 \cdot P(t) \cdot D(t) \cdot \sin(f_1 \cdot t + \phi_{P_1}) + a_1 \cdot C/A(t) \cdot D(t) \cdot \cos(f_1 \cdot t + \phi_c) \\
L2(t) &= a_2 \cdot P(t) \cdot D(t) \cdot \sin(f_2 \cdot t + \phi_{P_2})
\end{aligned}
$$

Since the Block II (1986) two encryption techniques were designed to restrict the civilian use of GPS signals:

- *S/A or Selective Availability:* Intentional satellite clock degradation (process-δ) and ephemeris manipulation (process-ε). The effect on horizontal positioning implies going from about 10 m (S/A=off) to 100 m (S/A=on). The process-δ acts directly over satellite clock fundamental frequency, which has a direct impact on pseudoranges to be calculated by user's receivers. The process-ε consists in truncating information related to the orbits. In May 2000 this technique was ordered to be switched off by the U.S. government. It is anticipated that the Block III does not even have the necessary elements to put it back on track (see Table 2.2 [32]).

Table 2.2: GPS Error Sources and Magnitudes

Error source	Error Magnitude (meters)	
	S/A on	S/A off
Selevtive Availability	24.0	0.0
Ionosphere	7.0	7.0
Troposphere	2.0	2.0
Clock	1.8	1.8
Ephemeris	1.4	1.4
Receiver Noise	0.6	0.6
Multipath	1.5	1.5
User Equivalent Range Error (UERE)	25.0	7.5
Typical Horizontal DOP (HDOP)	1.5	1.5
Stand-Alone Horizontal Accuracy (95%)	75	22.5

  - *A/S or Anti-Spoofing:* It consists in P code encryption by combining it with a secret W code, resulting the Y code, which is modulated over the two carriers L1 and L2. The purpose is to avoid the access of non authorized users to codes on both P1 and P2 frequencies, being solely C/A code (noisier) available over L1 [1].

- *Block IIR-M*

  With the new generation of satellites belonging to the Block IIR-M also become two new signals for civil and military uses.

  On the one hand, a signal called M-Code, exclusively for military use, is transmitted on L1 and L2 carriers. It was designed to further improve the anti-jamming and secure access of the military GPS signals. Being a military signal, there has been little information about it. Still, it is known that the M-code uses DSSS modulation with a 5,115 MHz chipping rate and a spread spectrum symbol that is two cycles of a 10.23 MHz square wave. This DSSS modulation variant is referred to as Binary Offset Carrier (BOC[4]).

Moreover, a new signal for civilian use was designed to be broadcast on L2 carried called L2C, centred at 1,227.60 MHz. The L2C signal is tasked with improving accuracy of navigation, providing an easy to track signal, and acting as a redundant signal in case of localized interference. L2C has a dataless signal component and the receiver is able to do Forward Error Correction (FEC). Data-free signal components are very useful in low Signal-to-Noise Ratio (SNR) environments. Since the navigation bits are not known a-priori, today's GPS receiver must square the received signal to strip the navigation bits. This squaring action achieves the intended purpose of removing the data modulation, but it also introduces squaring loss. Squaring loss arises simply because the received noise is also squared. It grows as the SNR decreases. Unfortunately, squaring loss is greatest in low SNR environments. L2C has its greatest potential to generate befits for dual frequency applications [33].

Unlike the C/A code, L2C contains two distinct PRN code sequences to provide ranging information; the Civilian Moderate length code (called CM), and the Civilian Long length code (called CL). The CM code is 10,230 bits long, repeating every 20 ms. The CL code is 767,250 bits long, repeating every 1,500 ms. Each signal is transmitted at 511,500 bits per second (bit/s); however, they are multiplexed together to form a 1,023,000 bit/s signal. L2C uses DSSS modulation with rectangular symbols and a 1.023 MHz chipping rate. ICAO decided against including L2C within the GNSS SARPs in 2002 because the L2 band is shared with radiolocation (radars), fixed services, and mobile services in some regions, and reception of L2C without interference from other services could thus not be ensured worldwide.

- *Block IIF*

  The signals of this Block are the newest signals that a GPS receiver can detect by the moment. The most prominent innovation is undoubtedly the design of a new signal for civilian use on a new carrier called L5, 1,176.45 MHz. The signal has also been named in the same way and is generated by a rectangular symbols DSSS modulation with a chipping-rate of 10.23 MHz. The presence of the pilot channel and the use of a faster chipping rate are the two features that are expected to improve GPS L5 tracking performance the most. Like the new L2 signal, the new L5 signal also

[4]Binary Offset Carrier (BOC) modulation is a square sub-carrier modulation, where a signal is multiplied by a rectangular sub-carrier of frequency f_{sc} equal or higher to the chip (CDMA) rate. Following this sub-carrier multiplication, the spectrum of the signal is divided into two parts, therefore BOC modulation is also known as a split-spectrum modulation. In practice may be generated, as the product of an ordinary DSSS signal using rectangular symbols and a square wave subcarrier.

provides a data free signal component to enhance operation at low signal to noise ratios. However, the L5 signal design did not have to resort to time multiplexing of the codes, because both the inphase and quadrature channels are available for civilian use. The correction of the ionospheric refraction for civil users is more accurate thanks to the L5 signal.

Located at 1,176.45 MHz, this signal falls in the middle of the worldwide used band called DME[5]. This band is also used for the Joint Tactical Information Distribution System (JTIDS) in the United States. As a result, the L5 noise floor will frequently be higher than thermal noise especially for aircraft at significant altitudes. Fortunately, the radiated power will be approximately four times greater than the current C/A signal power, and the U.S. FAA is prepared to reallocate DME frequencies in the U.S. if needed. The L5 signal is designed to a high received power level of -154.9dBW, while C/A and L2C are -158.5dBW and -160dBW respectively, so interferences or low reception due to the allocated band will be avoided [2].

- *Block III*

  The block III is expected to be operational from 2014 and one of the best achievements will be the introduction of another civil signal called L1C. The main attribute of this signal is the robustness that will add to the GPS, as well as the benefit provided to the signal acquisition and tracking and the faster TTFF (Time to First Fix). L1C signal will be transmitted over the L1 frequency and will be created using a BOC modulation with a 1.023 MHz chipping rate and timemultiplexed mixture of symbols that are derived from1.023 and 6.138 MHz square wave subcarriers [34]. The L1C signal consists of two main components; one denoted L1CP to represent a pilot signal, without any data message, and the L1CD that is spread by a ranging code and modulated by a data message. The data message on L1CD, denoted DL1C(t), includes SV ephemerides, system time, system time offsets, SV clock behaviour, status messages, and other data messages. Due to the nature of the signal, GPS will be more interoperable with Galileo E1 OS and also the FEC (Forward Error Correction) will improve lowers demodulation threshold. For the civil users, the accuracy in positioning will be much better combining the information of C/A, L2C, L5 and LC1 [35]. The frame will have interleaving, so it will minimize the effect of short fades and multipath. Summarising, when the Block III will be available, civil user will improve significantly the positioning accuracy of their 3rd generation GPS receivers. Also, as they will be compatible with the European Galileo System, a combination of both system will provide accuracies and robustness impossible to have by now with

[5]Band used by civil aviation for Distance Measuring Equipment (DME)

the normal GPS receivers. Also, the aviation will also be benefited by these improvements, as this additional Safety-of-Life (SoL) civilian signal will make GPS an even more robust navigation service for many aviation applications. Figure 2.6 shows the evolution on the GPS signals from Bock I until Block III, with the frequencies where they are allocated and the relative power the signals have.

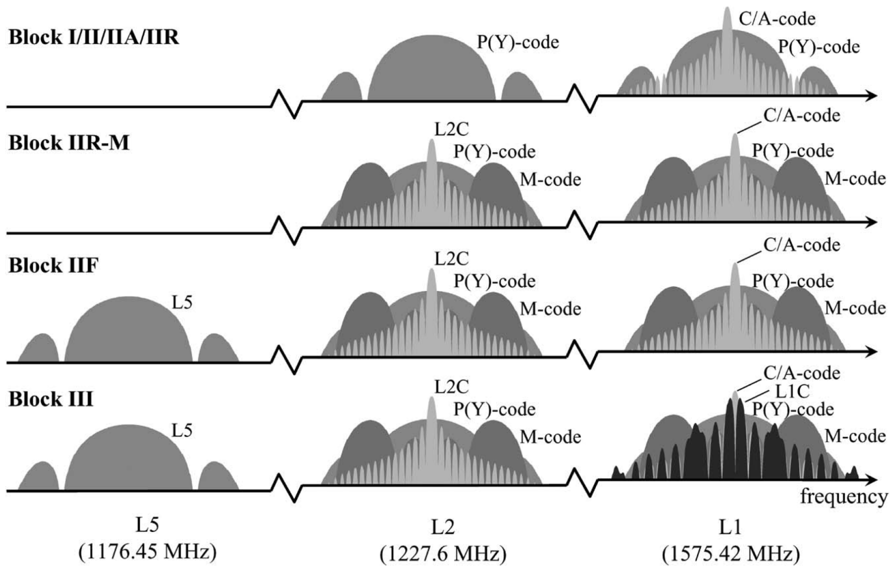


Figure 2.6: GPS signals evolution [2]

2.1.1.2 Control Segment

The Control Segment (CS) primarily consists of a Master Control Station (MCS) plus Monitor Stations (MS) and Ground Antennas (GA) at various locations around the world. The MCS is located at Air Force Base (AFB) in Colorado Springs, USA, while the monitor stations are located at Hawaii Kwajalein, Diego Garcia, Ascension and also at the Master Control Station, AFB. The mission of the MS is to receive all the transmitted signals by the satellites, save the received messages and transmit all the gathered information to the MCS. All monitor stations except Hawaii and Falcon AFB are also equipped with ground antennas (see Figure 2.7) in order to transmit the corrections to the satellites. The Control Segment includes a Prelaunch Compatibility Station (PCS) located at Cape Canaveral, USA, and a back-up MCS capability. The PCS primarily operates under control of the MCS to support prelaunch compatibility testing of GPS satellites via a cable interface. The PCS also includes an RF transmit/receive capability that can serve as a Control Segment ground antenna, if necessary [5].

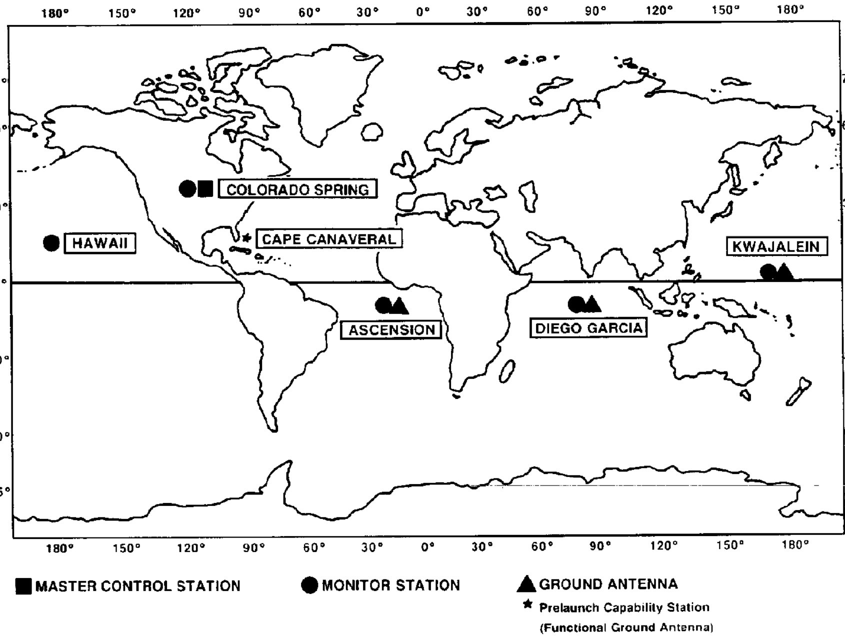


Figure 2.7: Control Segment elements [5]

The MSC constitutes the general control centre of the GPS system. This centre receives the information gathered by the Monitor Stations, calculates the exact orbit of each satellite, evaluates the necessary information for the proper operation of the system, and then sends the corrections to be incorporated in the navigation message transmitted by each satellite. The MCS is also responsible for detecting any faults and provide corrective measures, as well as to ensure the normal maintenance of the satellites. The MCS operates 24 hours every day of the year.

Corrections, as well as the updated almanac are transmitted to each satellite using the three ground antennas described above. The information provided also include messages concerning the operational status of the satellites. These ground antennas are also used to receive and transmit other control information. The information is transmitted in the S Band, at 1,783.74 MHz uplink and 2,227.5 MHz downlink [36]. Figure 2.8 graphically shows how the CS works.

The CS has been planned to establish up to three satellite contacts per day, which guarantees a sufficient accuracy to the system. However, in general, with only two daily contacts the degree of accuracy required is achieved. Each satellite is observed by the CS for more than 95% of the time. The only critical case in which the integrity of the system can be degraded is if, during the time when the satellite is not observed, there is a failure in the operation.

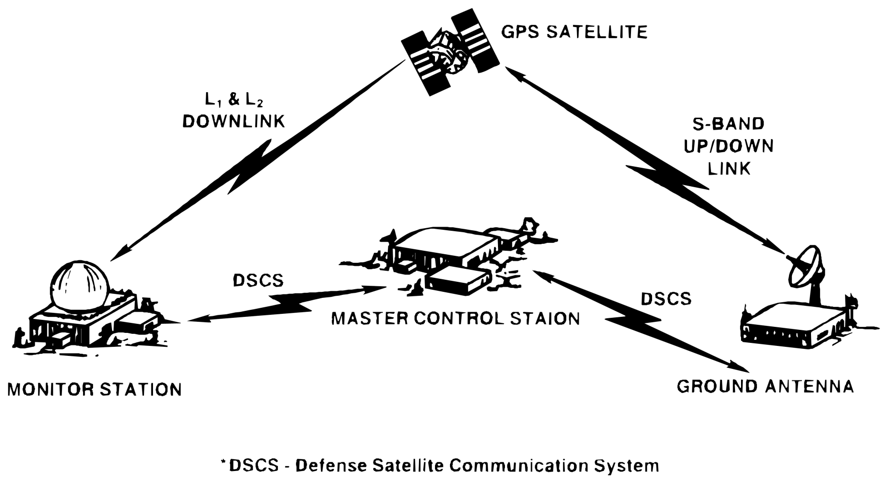


Figure 2.8: Control Segment communication process [5]

2.1.1.3 User Segment

The User Segment is formed by the GPS receivers. Its main function is to receive GPS satellite signals, to determine pseudoranges, and solve the navigation equations in order to get their coordinates and provide a very precise time.

The basic elements of a generic GPS receiver is an antenna with pre-amplification, a radio frequency section, a microprocessor, an intermediate-precision oscillator, a feeding source, a some memory for data storage, and an interface with the user. The calculated position will be referred to the phase centre of the antenna.

Figure 2.9 shows the generic GPS receiver tracking system.

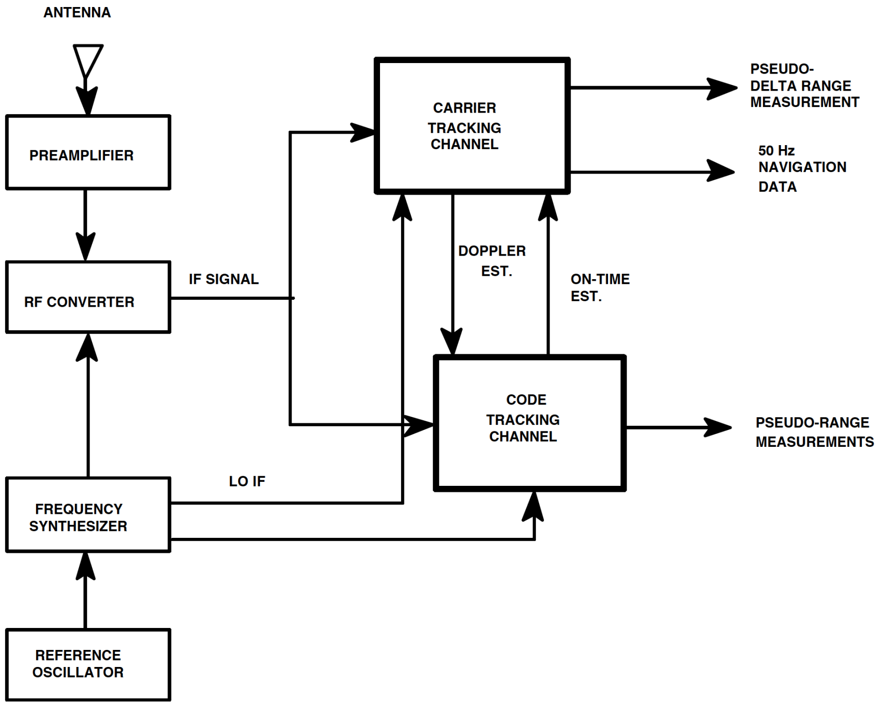


Figure 2.9: GPS Receiver tracking system [5]

Navigation Message

The navigation message consists of 25 frames of data, each frame consisting of 1,500 bits. Each frame is divided into 5 subframes of 300 bits each (see Figure 1-5). At the 50 Hz transmission rate, it takes 6 seconds to receive a subframe, 30 seconds to receive one data frame, and 12.5 minutes to receive all 25 frames. Subframes 1, 2, and 3 have the same data format for all 25 frames. This allows the receiver to obtain critical satellite-specific data within 30 seconds. Each subframe begins always with the telemetry word (TLM), which is necessary for synchronization. Then appears the transference word (HOW), whose mission is to enable rapid commutation from the C/A code to the P code [5].

The content of each of the subframes is the following (see Figure 2.10):

- *Subframe 1:* Contains information about the parameters to be applied to satellite clock status for its correction. These values are the coefficients that allow to convert time on board to GPS time. It also has data about satellite health condition and information about message ambiguity.
- *Subframes 2 and 3:* These subframes contain satellite ephemeris.
- *Subsection 4:* This subframe contains the ionospheric model parameters (to correct

the ionospheric refraction), UTC (Coordinated Universal Time) information, part of the almanac and indications of whether it is enabled on each satellite the Anti-Spoofing, A / S (which transform the P code in the encrypted code Y).

- *Subsection 5:* contains the almanac data and the status of the constellation. This allows a quick identification of which satellites are transmitting the received signals. 25 frames are needed to complete the almanac.

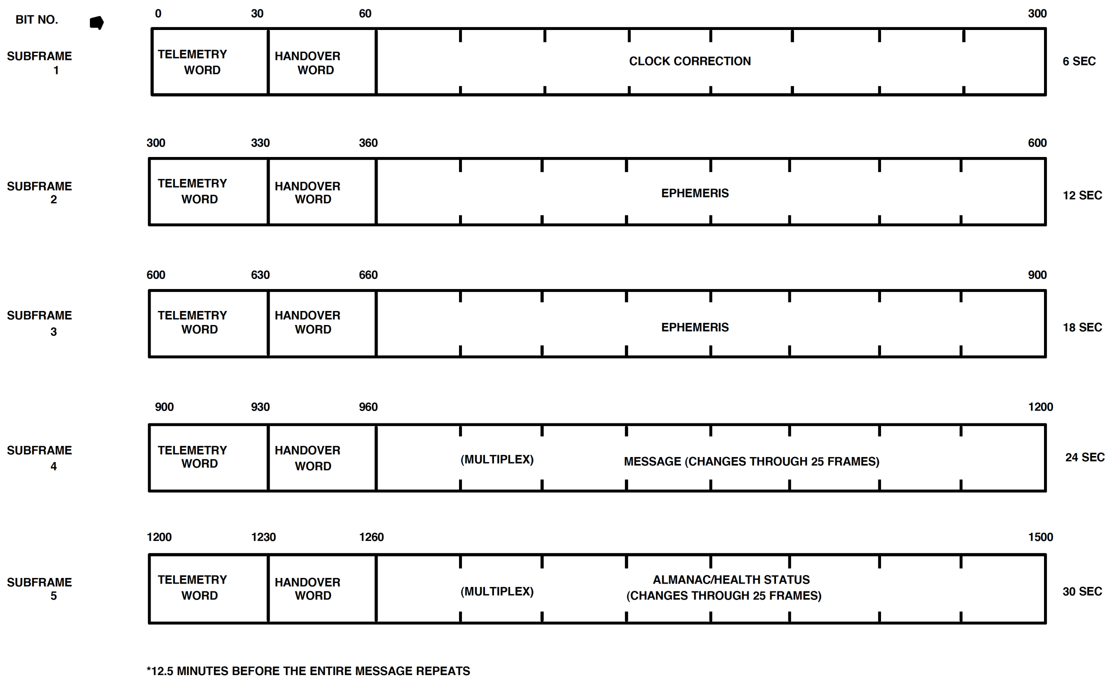


Figure 2.10: Navigation Message frame [5]

2.1.2 Position calculation by the receiver

The principle of working of the GPS receiver is based, like the old electronic navigation systems, on the mathematical principle of trilateration. Therefore, to calculate the position of a point will require the GPS receiver to accurately determine the distance that separates it from the satellites.

Using the mathematical principle of trilateration one can know the position where is located, and even track and locate the source of a radio wave transmission. The GPS system uses the same principle but instead of using circles and straight lines, it creates virtual or imaginary spheres to achieve the same objective.

From the moment the GPS receiver detects a radio frequency signal transmitted by a satellite from its orbit, it creates a virtual or imaginary sphere surrounding the satellite.

The satellite itself will act as the centre of the sphere whose surface is extended to the point or place where the receiver antenna is located, so the radius of the sphere is equal to the distance between the satellite and the GPS receiver. From that moment, the GPS receiver will measure the distances that separate at least two more satellites. It will have to calculate the time it takes for each signal to travel from the satellites to the point where it is located and to solve the corresponding mathematical equations.

Radiofrequency signals are composed by electromagnetic waves moving through space concentrically from the transmitting antenna, in a similar way as do the waves generated on the surface of the water when a stone is thrown. Because of this property, radio signals can be picked up from any point around a transmitting antenna. Radio waves travel at the speed of light (300,000 km/s) measured in a vacuum, making it possible to calculate the distance between a transmitter and a receiver if known the time it takes the signal to travel from one point to another.

To measure the time at which the satellite broadcasts the signal and the GPS receiver receives it, is needed that the clocks of the satellite and the receiver are perfectly synchronized. The satellite uses a cesium atomic clock, extremely accurate, but the GPS receiver has a quartz normal, not so accurate. To synchronize the GPS receiver clock, satellite broadcasts periodically a digital signal or pattern of control with the radiofrequency signal. This control signal reaches the GPS receiver always more delayed than normal radio frequency signal. The delay between both signals is equal to the time it takes the RF signal to travel from the satellite to the GPS receiver.

The distance between each satellite and the GPS receiver is calculated by different mathematical operations, this distance is called pseudorange. To make this calculation the GPS receiver multiplies the delay time control signal for the value of the speed of light. If the signal has travelled in a straight line, without any interference by the way, the mathematical result is the exact distance that separates the satellite receiver.

It is obvious that radio waves do not travel through a vacuum because of the gaseous mass that makes up the atmosphere, so their speed will not be exactly equal to that of light, but a little slower. There are also other factors may affect in the inaccuracy of the signal, such as local weather conditions, the angle between the satellite and the GPS receiver, relativistic effects, etc. To correct the effects of all these variables, the receiver uses complex mathematical models stored in memory. The results of the calculations are also complemented by the information about the corrections received by the satellites in order to get a more accurate position

To obtain the exact position, the GPS receiver must locate at least 3 satellites that serve as benchmarks. Actually that is not a problem because usually there is always 8 satellites within the "sight" of any GPS receiver. To determine the exact location of the orbit where the satellite should be at any given time, the receiver has an electronic almanac in its memory that contains the data. If the receiver does not have the almanac and position information stored, the receiver enters a "search the sky" operation that systematically searches the PRN codes until lock is obtained on one of the satellites in view. Once one satellite is successfully tracked, the receiver can demodulate the navigation message data stream and acquire the current almanac as well as the health status of all the other satellites in the constellation. To extract the satellite signal the receiver uses code correlation techniques. An internal replica of the incoming signal is generated and aligned with the received satellite signal. The receiver shifts the replica code to match the incoming code from the satellite. When the codes match, the satellite signal is compressed back into the original carrier frequency band. The process of the signal acquisition is shown in Figure 2.11.

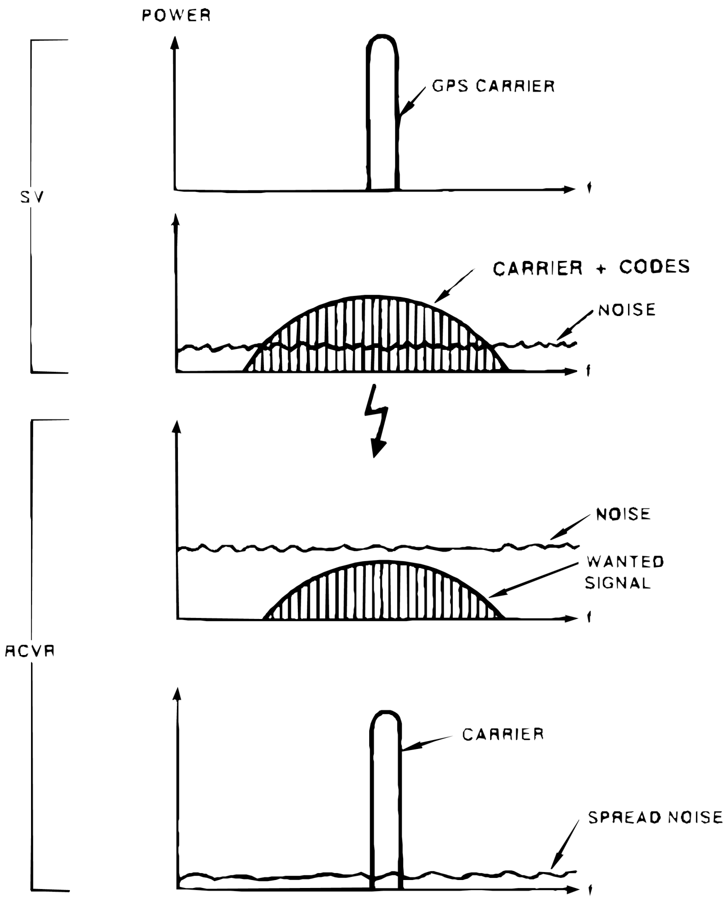


Figure 2.11: Signal Acquisition proces [5]

The principle of operation of GPS receivers could be summarised as follows (see Figure 2.12) [5]:

1. When the receiver detects the first satellite generates a virtual or imaginary sphere whose centre is the satellite itself. The radius of the sphere, i.e. the distance from its centre to the surface, will be the same between the satellite and the GPS receiver, which assumes then that is located at any point on the surface of the sphere. Obviously, the receiver is not able to precise in which of the countless points of the sphere is located.

2. Calculating the distance to a second satellite, the receiver generates another virtual sphere. The area previously created overlays that other, as a result, an imaginary ring through spheres intersection appear.

3. The receiver calculates the distance to a third satellite and generates a third virtual sphere. This area is cut by the ring previously created at a point in space and on the surface of the Earth. The receiver discriminates as a location the point situated in the space (in case of GPS that are not made for aviation) using mathematical resources and takes as a correct position the point on Earth.

4. Once the receiver runs the three above steps on your screen can show values for the coordinates of your position, i.e. latitude and longitude.

5. In order to detect the height in which the GPS receiver is located, or in case of the GPS receiver is not over the Earth surface, another satellite is needed to discriminate one of the two points of the three spheres intersection. Many receivers will track more than four satellites, but less than all-in-view, as a compromise between complexity, accuracy, and robustness. I has to be noticed that, an acquisition with 3 satellites will be also very inaccurate due to the fact that the receiver clock will not be synchronised accurately with the satellites clock.

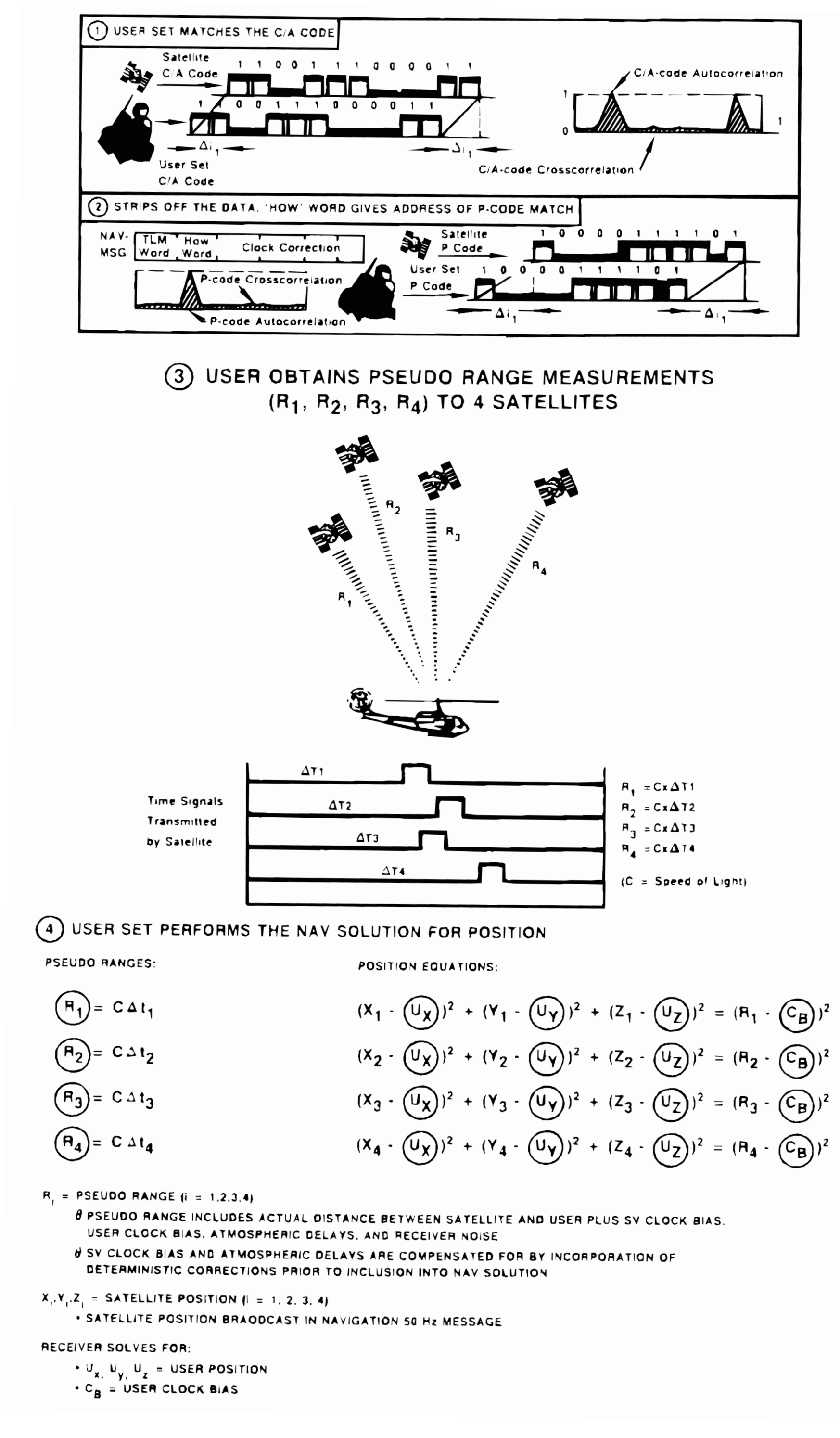


Figure 2.12: GPS Receiver Theory of Operation [5]

2.1.3 Problems in GPS

As mentioned previously, GPS is a positioning system with several problems due to the amount of errors that affect it. The most noticeable problem for the user is the poor accuracy in some conditions. There are also some limitations of the system as a result of the kind of signals that are used by the system. These signals can only be detected in outdoor conditions, and depending on the environment (tress, buildings, atmospheric conditions, etc.) the power signal can be too poor to be detected by the receiver. Due to this, the more adverse conditions the receiver has, the worse accuracy the positioning will be.

Another typical problem of the receivers is the inhability to synchronise the replica with the signal received. The clocks used in the receivers are not atomic, as a consequence, errors in synchronise affects the calculation of the pseudorange, which entails inaccuracy in positioning. A wider examination about the errors in GPS can be found in Chapter 3.

Regarding the techniques to improve the GPS accuracy, in Chapter 4 there is a deep description of them.

2.2 Global Navigation Satellite System (GLONASS)

GLONASS [37] (Russian: GLObalnaya NAvigatsionnaya Sputnikovaya Sistema; English: GLObal NAvigation Satellite System) is a Global Navigation Satellite System operated by the Russian Federation. This system was released only 4 years after the first GPS satellite was launched by the U.S. Firstly, the system was thought to be fully operational by the year 1991, but finally the whole constellation (24 satellites) was reached in December 1995 and begin to be fully operational the 18th January of 1996 [38]. The principles of working is very similar to the GPS. User equipment performs passive measurements of pseudoranges and pseudorange rate of four (three in case of not need the altitude) GLONASS satellites as well as receives and processes navigation messages contained within navigation signals of the satellites. The navigation message describes position of the satellites both in space and in time. Combined processing of the measurements and the navigation messages of the four (three) GLONASS satellites allows user to determine three (two) position coordinates, three (two) velocity vector constituents, and to refer user time scale to the National Reference of Coordinated Universal Time UTC(SU). The data ensuring of sessions scheduling for navigational determinations, selection of working "constellation" of SVs and detection of radiosignals transmitted by them, are transmitted as a part of the navigation message.

The problem of the short life of the satellites, add to the low investment the Russian Federation gave to the project because of its difficult economic situation during the 90s, were the main reasons to the degradation of the constellation to the point of only having 8 operational satellites in 2002. Nevertheless, in august 2001, the Russian Federation government adopted a long-term special program to improve the GLONASS system. The main purposes of this program were the reestablishment of the orbital segment by the year 2008, the modernisation of the navigation satellites (Uragan-M and Uragan-K) increasing the life time of them and improving the technology (new signals and frequencies) and also provide GLONASS with Search and Rescue (SAR) capabilities [39]. To this day, the initiative has been successful as the Uragan-M launch phase is finished and it is expected that the first Uragan-K launch will be on the beginnings of 2011.

2.2.1 GLONASS structure

The GLONASS system is composed of three main elements:

- Constellation of satellites (space segment)
- Ground-based control facilities (control segment)
- User equipment (user segment)

2.2.1.1 Constellation of Satellites

The constellation is thought to have 24 satellites, 8 in each of the 3 orbital planes, in order to get global coverage. However, there have been periods in which the constellation was not full, so there has been only fully coverage for Russia (12 satellites needed) or even less than this. The altitude of the orbits is 19,100 km, lower than the GPS orbits, and the eccentricity is 0. The period of each satellite is 11 hours 15 minutes and 44 seconds, and the inclination is 64.8^{o} relative to Earths equator.

Orbital planes are spaced at 120 degrees in longitude. There are eight satellites in each plane, which are evenly spaced at 45 degrees in phase. Moreover, the planes themselves are phase-shifted 15 degrees with respect to each other. Such an orbital configuration enables continuous and global coverage of the Earth's surface and near-Earth airspace, as well as an optimal spatial location of the satellites that increases position determination accuracy.

The current GLONASS satellites broadcast navigation signals in two subbands of L-band referred to as L1 and L2. A Frequency-Division Multiple Access (FDMA) design for the signals are utilized, with the L1 and L2 carrier frequencies given by:

$$\begin{aligned} f_{K1} &= f_{01} + K \cdot \triangle f_1 \\ f_{K2} &= f_{02} + K \cdot \triangle f_2 \end{aligned}$$

Where $f_{01} = 1602MHz$, , $f_{02} = 1246MHz$, $\triangle f_1 = 0.5625MHz$, $\triangle f_2 = 0.4375MHz$ and K is the channel number. The channel number was initially designed to be from 0 to +13, however, in order to protect the radio astronomy service in the 1,610.6-1,613.8 MHz and 1,660-1,670 MHz, Russia committed to not use the upper channels, so the range of channels numbers were redesigned from -7 to +6 [2] (see Table 2.3 [37]). Currently, all the satellites are transmitting into this range. To overcome the problem of having more satellites than frecuency slots, two antipodal satellites can use the same frecuency(see Figure 2.13), as they will never broadcast different signals over the same frecuency to the same receivers. The level of the received RF signal at the output of a 3dBi linearly polarized antenna is not less than (-161) dBW for L1 sub-band and (-167) dBW for L2 sub band provided that the satellite is observed at an angle of 5° or more.

Table 2.3: GLONASS carrier frequencies in L1 and L2 sub-bands

No. of channel	Nominal value of frequency in L1 sub-band (MHz)	No. of channel	Nominal value of frequency in L2 sub-band (MHz)
06	1,605.375	06	1,248.625
05	1.604.8125	05	1,248.1875
04	1,604.25	04	1,246.75
03	1,603.6875	03	1,247.3125
02	1,603.125	02	1,246.875
01	1,602.5625	01	1,246.4375
00	1,602.0	00	1,246.0
-01	1,601.4375	-01	1,245.5625
-02	1,600.8750	-02	1,245.1250
-03	1,600.3125	-03	1,244.6875
-04	1,599.7500	-04	1,244.2500
-05	1,599.1875	-05	1,243.8125
-06	1,598.6250	-06	1,243.3750
-07	1,598.0625	-07	1,242.9375

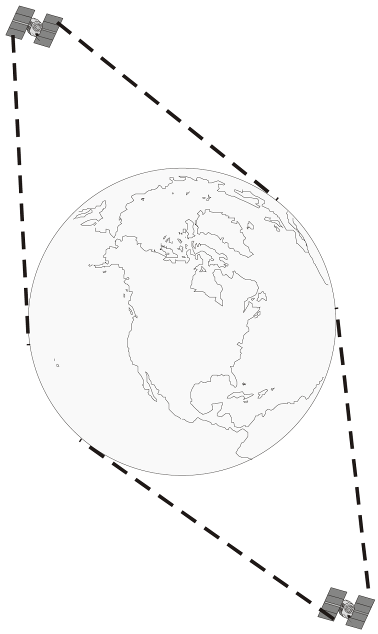


Figure 2.13: GLONASS Antipodal Satellites

The GLONASS Satellites broadcast two different signals depending on the service given, the Standard Accuracy Signal (for civil users) and the High Accuracy Signal (for the Russian Ministry of Defence and authorised users), both modulated as a Direct-Sequence Spread Spectrum (DSSS). The first one is generated using a lenght-511 maximal sequence and a 0.511 MHz chipping rate, whereas the second one has a 5.11 MHz chipping rate. Navigation data are modulated upon the signals at 50 bps, without Forward Error Correction (FEC).

The former Union of Soviet Socialist Republics offered GLONASS for civil aviation use, free of direct user fees, to the International Civil Aviation Organization (ICAO) in 1998, and on May 18, 2007, the Russian Federation signed a decree reiterating the offer to provide GLONASS civil signals to the world.

Concerning the satellites, two types of satellites has been launched up to now and another one is expected to be launch in the beginnings of 2011. Since the first launch in 1982, several changes in the satellites has been made. The firsts satellites launched were called Uragan (or also GLONASS) with an operational life span of 3-4 years. Due to this, the establishment of a fully operational constellations became a hard task for the Russian Federation, as they need to replace the satellites too often. These satellites broadcasted the High accuracy signals in both L1 and L2 bands, but they only broadcasted the civil signal (Standard Accuracy Signal) on the L1 band[6].

The second generation of satellites launched from December 2003 is called Uragan-M

(Modernised Uragan or GLONASS-M) (see Figure 2.14). Two enhances characterise this new generation, the first is the improvement in the operational life span from 3-4 years to 7 years; the second is the broadcast of the Standard Accuracy Signal in the L2 band. Another highlight is the fact of the more accuracy in the orientation of the solar panel, giving the satellite more efficiency. The atomic clock for these satellites is a Celsium (Cs) clock.

Figure 2.14: Uragan-M overall view [6]

The last generation of satellites is called Uragan-K (or GLONASS-K) (see Figure 2.15) and is expected to be in orbit by the beginnings of 2011. The most outstanding enhancement is the introduction of a new open signal in a new band called L3 (1,198-1,213 MHz). The civil L3 signals will use DSSS modulation with rectangular chips, like the L1 and L2 civil GLONASS signals, but will employ a much higher chipping rate on the order of 4 MHz. This signal will let the civil users to notably improve the accuracy. These satellites will also improve the life time up to 10 years, and will have Cesium and Rubidium atomic clocks. Concerning the weight, it will be reduced to the half of the previous satellites, as a result, 6 satellites would be able to be launched simultaneously with the same launcher.

Figure 2.15: Uragan-K overall view [6]

A recent development in GLONASS is that CDMA signals, in addition to the FDMA signals described above, are being considered for the GLONASS-K satellites and beyond. The FDMA approach for GLONASS, with each signal on a separate carrier frequency, leads to slightly more complex user equipment. Furthermore, group delay variations across the passband of receivers can result in biases in the measurements made from one signal to the next. These biases can impact the achievable accuracy unless sophisticated calibration techniques are employed. CDMA GLONASS signals at 1,575 and 1,176 MHz are tentatively planned for GLONASS-K and beyond, utilizing signal designs similar to the GPS L1C and L5 signals.

Figure 2.16 shows the evolution of the FDMA signals in GLONASS satellites from the firsts Uragan (GLONASS) satellites until the Uragan-K (GLONASS-K) satellites.

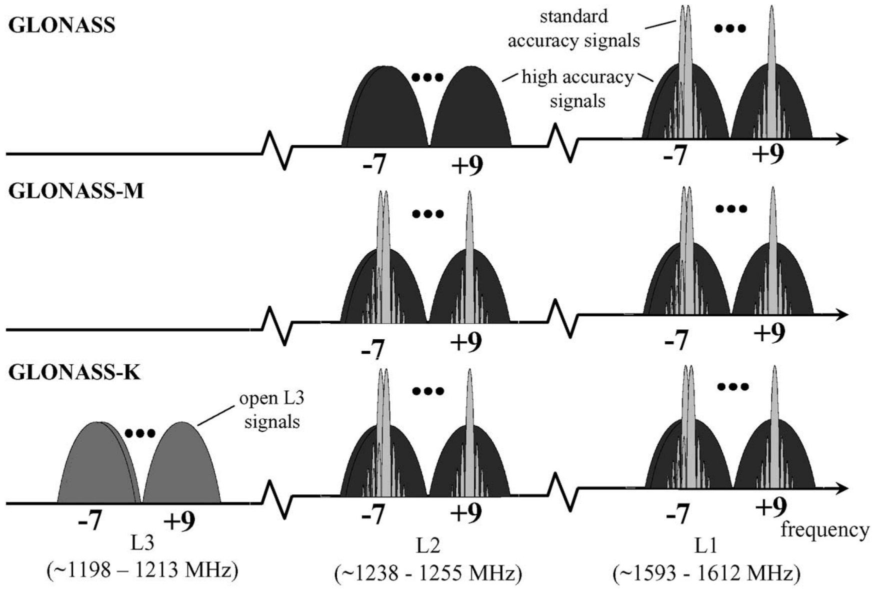


Figure 2.16: FDMA signals evolution in GLONASS [2]

By the time this thesis was written, a total of 26 satellites where in constellation, 22 of them were operational whereas 4 were in commissioning phase (maintenance). One of the 22 operational satellites was only operating in the L1 band only. By this time, there were no spares due to the fact that some of the satellites in constellation were in maintenance. Figure 2.17 shows the status of the constellation reported by the Federal Space Agency of Russia the 2nd of February of 2011 [39].

Total satellites in constellation	26 SC
Operational	22 SC
In commissioning phase	-
In maintenance	4 SC
Spares	-
In decommissioning phase	-

GLONASS Constellation Status at 02.02.2011 based on both the almanac analysis and navigation messages received at 10:00 02.02.11 (UTC) in IAC PNT TsNIImash

Orb. pl.	Orb. slot	RF chnl	# GC	Launched	Operation begins	Operation ends	Life-time (months)	Satellite health status		Comments
								In almanac	In ephemeris (UTC)	
I	1	01	730	14.12.09	30.01.10		13.6	+	+ 08:59 02.02.11	In operation
	2	-4	728	25.12.08	20.01.09		25.3	+	+ 08:59 02.02.11	In operation
	3	05	727	25.12.08	17.01.09	08.09.10	25.3			Maintenance
	5	01	734	14.12.09	10.01.10		13.6	+	+ 10:30 02.02.11	In operation
	6	-4	733	14.12.09	24.01.10		13.6	+	+ 10:30 02.02.11	In operation
	7	05	712	26.12.04	07.10.05		73.3	+	+ 08:59 02.02.11	In operation
	8	06	729	25.12.08	12.02.09		25.3	+	+ 08:59 02.02.11	In operation
II	9	-2	736	02.09.10	04.10.10		5.0	+	+ 08:59 02.02.11	In operation
	10	-7	717	25.12.06	03.04.07		49.3	+	+ 08:59 02.02.11	In operation
	11	00	723	25.12.07	22.01.08		37.3	+	+ 08:59 02.02.11	In operation
	12	-1	737	02.09.10	12.10.10		5.0	+	+ 10:00 02.02.11	In operation
	13	-2	721	25.12.07	08.02.08		37.3	+	+ 10:30 02.02.11	In operation
	14	-7	722	25.12.07	25.01.08		37.3	+	+ 10:30 02.02.11	In operation (L1 only)
			715	25.12.06	03.04.07	24.10.10	49.3			Maintenance
	15	00	716	25.12.06	12.10.07		49.3	+	+ 10:38 02.02.11	In operation
	16	-1	738	02.09.10	11.10.10		5.0	+	+ 08:59 02.02.11	In operation
III	17	04	714	25.12.05	31.08.06		61.3	+	+ 08:59 02.02.11	In operation
			718	26.10.07	04.12.07	29.11.10	39.3			Maintenance
	18	-3	724	25.09.08	26.10.08		28.3	+	+ 09:15 02.02.11	In operation
	19	03	720	26.10.07	25.11.07		39.3	+	+ 10:31 02.02.11	In operation
	20	02	719	26.10.07	27.11.07		39.3	+	+ 10:31 02.02.11	In operation
	21	04	725	25.09.08	05.11.08		28.3	+	+ 10:31 02.02.11	In operation
	22	-3	731	02.03.10	28.03.10		11.1	+	+ 10:30 02.02.11	In operation
			726	25.09.08	13.11.08	31.08.09	28.3			Maintenance
	23	03	732	02.03.10	28.03.10		11.1	+	+ 08:59 02.02.11	In operation
	24	02	735	02.03.10	28.03.10		11.1	+	+ 08:59 02.02.11	In operation

Figure 2.17: Constellation Current Status

Ground-Based Control Facilities

As in the GPS Control Segment, this GLONASS segment is in charge to keep the system updated in order to guarantee a good service. The Ground Control Segment (GCS) is composed of the System Control centre (SCC), located in Moscow Territory, and several Telemetry, Tracking, and Control stations (TT&C) distributed throughout the Russian territory [6] (see Figure 2.18). In the GCC there is also the Central Synchronizer (CS), the Navigation Signal Phase Control System (PCS) and a Navigation Field Control Equipment (NFCE), which is also located in Komsomolsk-on-Amur [38]. The main tasks of the GCS are:

- Monitoring of the orbital constellation's normal operation
- Continuous adjustment of satellite orbit parameters
- Generation and uploading of time-tagged programmes, control commands, and especial information

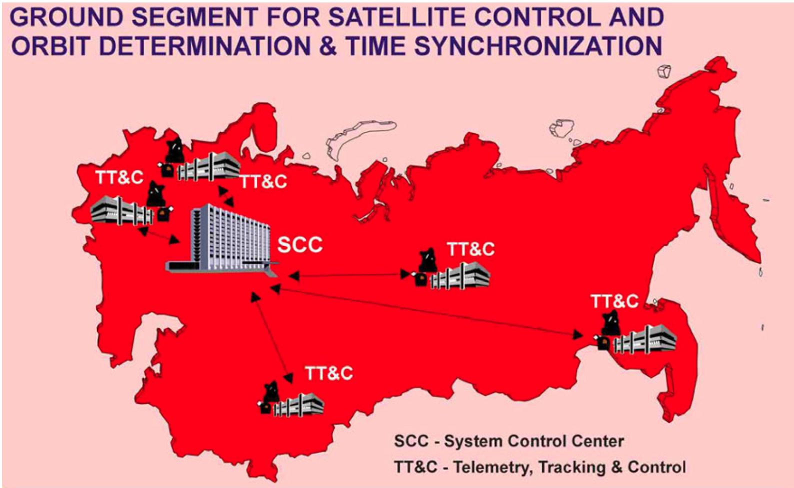


Figure 2.18: Ground-Based Control Facilities [6]

All the processes done by the GCS must be synchronized to be successful, the part of the segment in charge of that is the Central Synchronizer, a stationary ultra-stable hydrogen frequency standard, which is used as the basis for GLONASS time scale generation.

The monitoring is based in the principle of comparison between the information received by the satellites and the precise coordinates that the different stations have registered. Once the stations have evaluated the differences between the estimated coordinates and the high-accuracy geodetics positions they have registered, a signal is transmitted to the satellites in order to correct the navigation message. These data are loaded at satellite every day [38] (on-board timing scale synchronism data are loaded at every rotation, which is two times per 24 hours).

Regarding the navigation message, this is transmitted as a pattern of digital data that are coded by Hamming code and transformed into relative code. Structurally the data pattern is generated as continuously repeating super frames. A Superframe consists of the frames, and a frame consists of the strings.

The boundaries of strings, frames and Superframe of navigation messages from different GLONASS satellites are synchronized within 2 milliseconds.

The superframe has duration 2.5 minutes and consists of 5 frames. Each frame has duration 30 seconds and consists of 15 strings. Each string has duration 2 seconds. Within each frame a total content of non-immediate data (almanac for 24 GLONASS system satellites) are transmitted [37].

Concerning the content of the navigation message, it is not too much different as the GPS navigation message. Both messages have immediate and non-immediate data depending on the subframe.

The immediate data relate to the GLONASS satellite which broadcasts given RF navigation signal and include:

- Enumeration of the satellite time marks
- Difference between onboard time scale of the satellite and GLONASS time
- Relative difference between carrier frequency of the satellite and its nominal value
- Ephemeris parameters and the other parameters

The non-immediate data contain almanac of the system including:

- Data on status of all satellites within space segment (status almanac)
- Coarse corrections to onboard time scale of each satellite relative to GLONASS time (phase almanac)
- Orbital parameters of all satellites within space segment (orbit almanac)
- Correction to GLONASS time relative to UTC(SU) (formerly Soviet Union and now Russia) and the other parameters

User terminals

The User Segment consists of equipment (such as a NovAtel OEMV family receiver (see Figure 2.19) that tracks and receives the satellite signals [40]. This equipment must be capable of simultaneously processing the signals from a minimum of four satellites to obtain accurate position, velocity and timing measurements. Like GPS, GLONASS is a dual military/civilian-use system. The system's potential civil applications are many and mirror those of GPS.

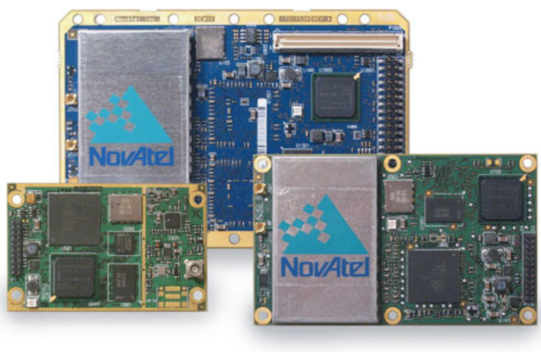


Figure 2.19: NovAtel OEMV Family receivers [7]

2.2.2 GLONASS & GPS Comparison

Table 2.4 shows the main characteristics of each of the systems.

Table 2.4: GLONASS and GPS technical specifications

Parameter	Detail	GLONASS	GPS
Satellites	Number of satellites (nominal)	21 + 3 spares	21 + 3 spares
	Number of orbital planes	3	6
	Orbital plane inclination (degrees)	64.8	55
	Orbital radius (km)	25,510	26,560
Signals	Fundamental click frequency (MHz)	5.0	10.23
	Signal separation technique	FDMA	CDMA
	Carrier frequencies (MHZ) - L1	1,598.0625-1,609.3125	1575.42
	Carrier frequencies (MHZ) - L2	1,242.9375-1,251.6875	1227.60
	Code clock rate (MHz) - C/A	0.511	1.023
	Code clock rate (MHz) - P	5.11	10.23
	Code length (chips) - C/A	511	1,023
	Code length (chips) - P	$5.11 \cdot 10^6$	$6.187104 \cdot 10^{12}$
C/A-code Navigation Message	Superframe duration (minutes)	2.5	12.5
	Superframe capacity (bits)	7,500	37,500
	Superframe reserve capacity (sec.)	~ 620	$\sim 2,750$
	Word duration (sec.)	2.0	0.6
	Word capacity (bits)	100	30
	Number of words within a frame	15	50
	Thechnique for specifying satellite ephemeris	Geocentric Cartesian coordinates and their derives	Kleperian orbital elements and perturbation factors
	Time reference	UTC(SU)	UTC(USNO)
	Position reference (geodetic datum)	PZ-90	WGS84

2.3 Galileo System

Galileo is the European GNSS currently being built by the European Union (EU) and European Space Agency (ESA) providing a highly accurate, guaranteed and global positioning service under civilian control. By now, the system is compatible with GPS and GLONASS. Furthermore, there are intentions to extend the compatibility to other navigation systems such as COMPASS, QZSS or IRNSS [41].

Galileo has been designed to offer two types of service, the navigation and the Search and Rescue (SAR) service. Regarding the navigation service, there are four different services on different levels of performance.

Open access service: Designed to offer navigation service for the most of users. This service is free for the user and the positioning and timing is not as accurate as other navigation services offered by Galileo. This service can be compared with the Standard Positioning Service offered by GPS.

Commercial service: The signal is encrypted due to the fact this service is not free. The highlights of this category is the high accuracy and that the service is guaranteed.

Safety of Life service: Is composed by the open service with integrity added by providing timely warnings to the users when it cannot guarantee to meet certain margins of accuracy.

Public regulated service: Like the commercial service, is encrypted to control the access to specific users requiring a high continuity of service.

The SAR service is characterised by the near real-time access to the information. The positioning is precise and return link feasible.

Table 2.6 shows the performance requirements for the Galileo Open and Safety-of-Life Services [2].

Table 2.6: Performance Requirements for the Galileo Open and Safety-of-Life Services

Galileo Services	Open service	Safety-of-Life service
Coverage	Global	Global
Accuracy (95%)	H: 15 m V: 35 m (single frequency) H: 4 m V: 8 m (dual frequency)	H: 4 m V: 8 m (dual frequency)
Availability	99.8%	99.5%
Alert limit	N/A	HAL: 40 m VAL: 20 m
Time to Alert	N/A	6 s
Integrity Risk	N/A	$2 \times 10^{-7}/150$ s
Continuity Risk	N/A	$8 \times 10^{-6}/15$ s
Certification and Service Guarantees	No	Yes

2.3.1 Galileo Architecture

Similar to any other GNSS, Galileo is composed by three segments, the space, ground and user segment as shows Figure 2.20.

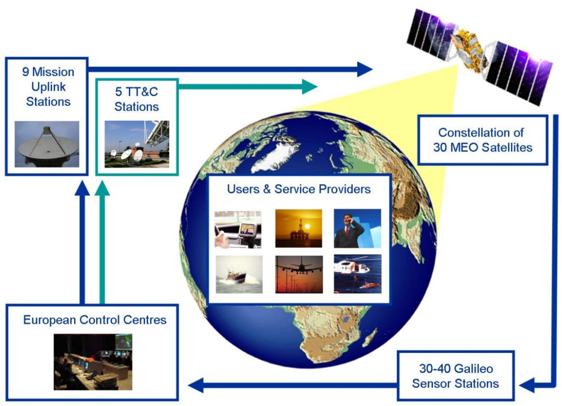


Figure 2.20: GALILEO Architecture [8]

2.3.1.1 Space segment

The satellites, in charge of broadcast the signals to the elements of the ground segment and to the end users, compose the Space Segment. The system is designed to work with

30 satellites (27 operation and 3 spares) distributed in three circular MEO planes at a nominal average orbit semimajor axis of 29,601.297 km, with an inclination of 56º with reference to the equatorial plane in a Walker 27/3/1 configuration (see Figure 2.21) [42].

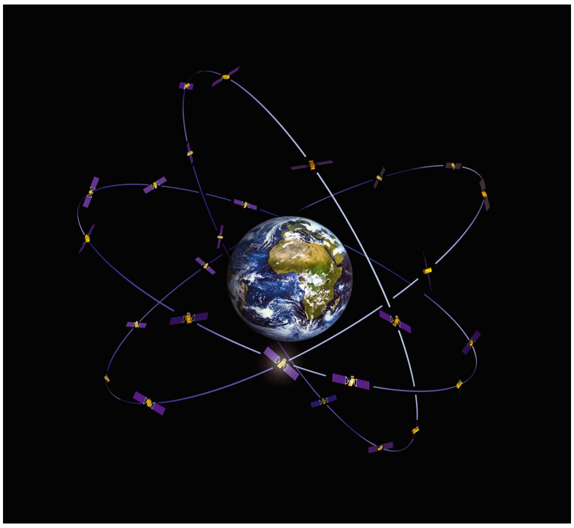


Figure 2.21: Galileo Constellation [9]

The main design drivers for the constellation were:

- Provision of high quality services on a global base
- Robustness of constellation design in the context of service availability
- Quality of service and high service reliability in case of satellite failures. A further design driver was the visibility of Galileo satellites and the related constellation performance for commercial and mass market services [9].

Two satellite prototypes were launched in 2005 and 2008 called GIOVE A and GIOVE B [43, 44] respectively. The estimated life time of each was around 2-3 years, but by 2011 they still working correctly, which means a great achievement for the ESA. Both satellites are part of the Galileo test mission in order to provide experimental results based on real data to be used for risk mitigation for the In-Orbit Verification (IOV) satellites that will follow on from the testbeds. This second phase of Galileo (IOV) is scheduled for the beginning of 2011 by the launch of two new satellites [45]. As mentioned before, the satellites must broadcast the signals as well as receive the corrections transmitted by the ground segment. Each Galileo satellite will broadcast 10 different navigation signals making it possible for Galileo to offer the Open (OS), Safety-of-Life (SOL), Commercial (CS) and Public Regulated services (PRS). The open services are realized by using the signals at L1, E5a and E5b, whether data or pilot (no data signals). Several combinations are also possible, such as a dual frequency service based on using L1 and E5a (for best ionospheric error cancellation) or single frequency services (at L1, E5a, E5b or E5a and E5b together) in which case the ionospheric error is removed using a model, and even triple frequency services using all the signal together (L1, E5a and E5b), which can be exploited for very precise, centimetric applications. The signals are centred in three different frequency bands, L1 (1,575.42 MHz), E6 (1,278.75 MHz) and E5 (1,191.795 MHz), providing a wide bandwidth for the transmission of the Galileo signals. These bands are included in the allocated spectrum for Radio Navigation Satellite Services (RNSS) and/or Aeronautical Radio Navigation Services (ARNS) (see Figure 2.22). The E6 signals are designed for PRS and CS services. The navigation data includes the ephemeris, time and clock correction parameters, service parameters and the almanac, very similar to the other GNSS described above [46]. The signals specifications can be checked in [41].

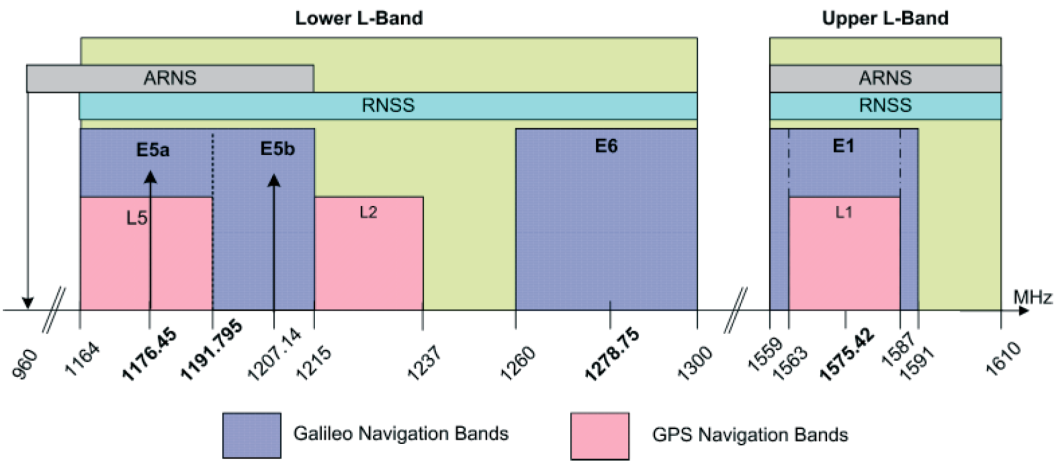


Figure 2.22: Galileo Frequency Plan

2.3.1.2 Ground Segment

The ground segment of Galileo is in charge of:

- Perform the measurement and monitoring of the satellites
- Time synchronization
- Uplink Navigation Messages to the satellites
- Determine and disseminate the integrity status of the system
- Continuously acquisition of relevant system information

- Enable permanent access to the satellites at any time

The elements needed to achieve these objectives are:

- About 30 GALILEO Sensor Stations (GSS) providing the instantaneous position of each satellite. Each GSS will be equipped with three parallel reception channels:
  - One channel for the determination of orbit data and clock synchronization
  - A second for the determination of integrity
  - A third redundant channel
- Nine Mission Uplink Stations (ULS) equipped with a total of 31 (up to four per site) C-band antennas. These stations will uplink the navigation and integrity data from the control centre to the satellites.
- Five Telemetry, Telecommand and Control (TT&C) stations equipped with S-band antennas to provide a secure exchange of data between the control centres and the satellites.
- Galileo Control Centres (GCC), is the core of the GS, where all the information gathered by the GSS is processed to provide the Navigation Message and the corrections to the ULS.
- Network to connect all the ground segment elements by radio or wired communication links [9].

2.3.1.3 User Segment

Due to the fact that the system is not operable for the end user, there are not commercial receivers available by the moment. Even though, some Galileo receivers have been implemented to perform tests with the signals broadcasted by the GIOVE satellites.

When Galileo will be fully operational, it is expected that receivers will combine Galileo, GPS and GLONASS signals in order to get a more accurate position.

2.4 Other systems

In this section are described three positioning systems that are currently being developed in different areas of the world. These three projects are less ambitious than the three main systems described in Sections 2.1, 2.2 and 2.3, as they are developed to provide regional coverage. Nevertheless, there is the possibility that, in a long-term future, some of them could provide global coverage.

2.4.1 COMPASS

COMPASS [11] (also known as Beidou-2) is the name of the Chinese Global Navigation Satellite System currently under development. The name Beidou-2 becomes from the first project implemented by the Chinese government called Beidou1 whose objective is to be a Wide Area Positioning System. COMPASS is not an extension of this first system, but a new GNSS based in the same principles as GPS, GLONASS or GALILEO.

Beidou-1, comprises three payloads on geosynchronous satellites. The system coverage of Beidou-1 is 70° – 145° E (longitudes), 5°-55° N (latitudes). Namely, east to the east of Japan, west to Kabul, Afghanistan, South to the Nansha Islands and north to the Lake Baikal in Russia, covering the whole territory of China, the West Pacific Ocean, Japan, the Philippines, India, Mongolia, Southeast Asia and other neighbouring countries and regions. Despite all the regions covered, in terms of access and users, China is the most favoured. During the 2000 and 2003, the three satellites were launched (called Beidou1-A, Beidou1-B and Beidou1-C) (see Table 2.7) [10].

Table 2.7: Satellites of Beidou-1

Name	**Position**	**Perigee**	**Apogee**	**Inclination**
Beidou1-A	140º E	35,722 km	35,803 km	0.10º
Beidou1-B	80º E	35,753 km	35,821 km	0.00º
Beidou1-C	110.5º E	35,760 km	35,836 km	0.30º

Besides positioning, Beidou-1 systems can also be employed in the transmission of short messages, which clearly differs from the other systems mentioned above. The satellites are used to broadcast the signal transmitted by the ground or user segments. The Ground Segment monitors the constellation status, as well as receive the signals from the users broadcasted by the satellites to check whether the users are authorised to use the system or not. In case of acknowledge the authorisation, the answer is transmitted to the user terminal. The frequency of messages received varies depending on the class of authorised user. Due to the principle of working of the system, the number of users is limited. The systems architecture is shown in Figure 2.23.

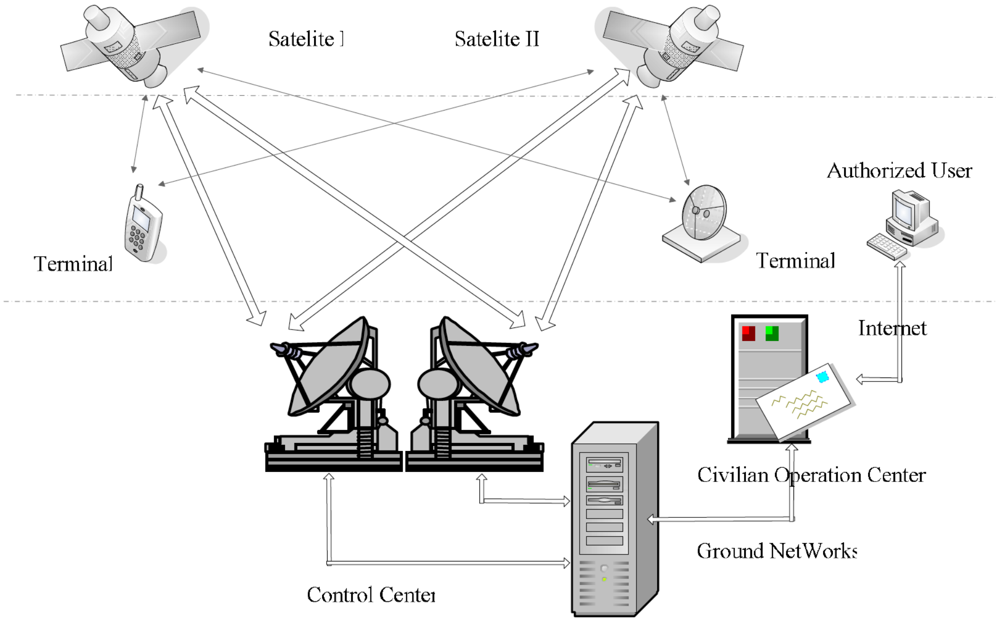


Figure 2.23: Beidou-1 architecture [10]

Compass system (Beidou-2) has been designed as a GNSS. The full operational system will have 30 medium earth orbit (MEO) satellites and 5 geostationary orbit (GEO) satellites. The MEO satellites will operate in six orbital planes to provide global navigation coverage [47]. Regarding the signals, like in GPS and Galileo, will be CDMA with binary or quadrature phase shift keying. Figure 2.24 shows the frequency bands used by COMPASS.

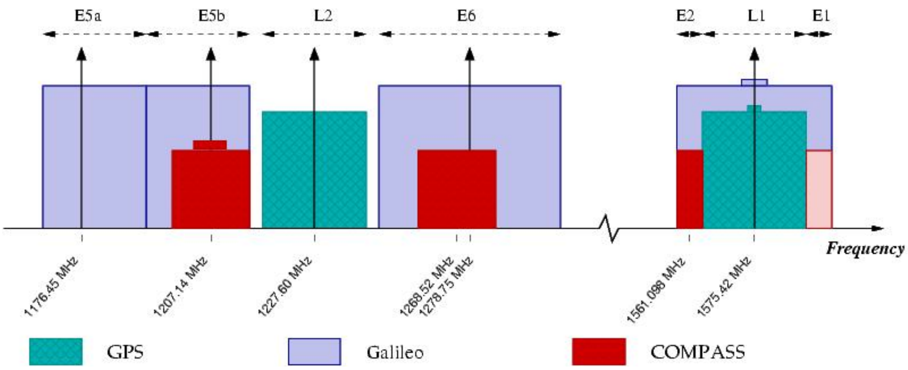


Figure 2.24: COMPASS signals frequency bands [11]

2.4.2 Indian Regional Navigation Satellite System (IRNSS)

Indian Regional Navigation Satellite System (IRNSS) [48] is an independent regional navigation system developed by the Indian government. The main objectives why the system was designed are:

- To provide reliable Position, Navigation and Timing services over India and its immediate neighbourhood.
- To provide fairly good accuracy to the user.
- The constellation is seen by user all the time.
- Integrity and ionospheric correction messages to user.

In order to reach these targets IRNSS has been designed to work with 7 satellites, 3 GSO satellites (at 34º, 83º and 131.5º E) and 4 Inclined GSO satellites. The first satellite is expected to be launched by the second half of 2011, and the constellation would be completed by mid 2014. The system, will also have a Ground Segment similar to the GPS or Galileo Systems.

IRNSS has been also designed to be compatible with the navigation systems that already exist, for this reason the frequency bands used are allocated in the bands used by the other systems. Two types of services will be available in IRNSS, one for authorised users and the other for civil users. The Standard Positioning Service will broadcast signals in BPSK modulation at 1 MHz in the L5 and S Bands. The other type, called Restricted Services for Special Users, will use signals in BOC(5,2) modulation in the same bands [49].

2.4.3 Quasi-Zenith Satellite System (QZSS)

The Quasi-Zenith Satellite System (QZSS) [50] is a regional space-based positioning system receivable within Japan that uses a constellation of satellites placed in multiple orbital planes. The system covers regions in East Asia and Oceania centring on Japan and is designed to enable users in the coverage area to receive QZS signals from a high elevation angle at all times. The system is also designed to enhance the GPS services in the QZSS coverage are by:

- Availability enhancement (improving the availability of GPS signals)
- Performance enhancement (increasing the accuracy and reliability of GPS signals)

To minimize changes to specifications and receivers designs, the system is compatible with GPS signals. The first satellite was launched on the 11th of September 2010 [50], and is expected to complete the whole constellation by 2013 [51].

2.5 Problems in positioning systems

Positioning systems have several sources of error, for this, the accuracy data given previously must be considered as a theoretical accuracy. Nowadays, GPS is the best system in positioning, due to the fact that the actual coverage is global and also because the GPS receivers industry has invested large amounts of money in order to investigate how to accurate more and more the positioning. Furthermore, many techniques to improve the accuracy have been developed during the last decades, providing the civil user unexpected accuracies in positioning. In Chapter 4 there is a description of the techniques to improve the GPS accuracy, also called, *Augmentation Systems*.

The most important competitors of GPS in short-term are GLONASS and Galileo. This last is expected to be even better than GPS for civil users, due to the fact that any Armo does not control it, and so, it has not been developed for military purposes. The combination of both systems, GPS and Galileo, in the same device, will provide the user an accuracy in positioning higher than with only GPS.

About the Asian positioning systems, notice that the regions under coverage of these systems will be benefit with more availability of signals, as well as these countries will not depend on the U.S.A. to use a positioning system.

Regarding the problems affecting the positioning systems described previously, taking into account that the principle of working is the same in each and every of them, the reader can get a global idea of how they affect the positioning systems reading the Chapter 3, where all the GPS errors are examinated.

Part II

GPS accuracy

Chapter 3

GPS Errors

Focusing this survey on the GPS system and before describing the techniques for improving accuracy, it is necessary to analyse which are the errors and how they affect the calculation of the position by the GPS receiver.

GPS positioning accuracy is limited by measurement errors that can be classified as either common mode or non-common mode. Common mode errors have nearly identical effects on all receivers operating in a limited geographic area ($<$ 50 km). Non-common mode errors are distinct even for two receivers with minimal antenna separation. The common mode pseudorange errors have a typical standard deviation on the order of 25 meters for civilian receivers. The common mode errors are smooth, continuous signals with correlation times on the order of 300 seconds. The non-common mode errors are dominated by multipath and receiver noise. Code multipath (i.e. multipath errors on the pseudo-range derived from the pseudo-random noise code (PRN)) has a standard deviation of a few meters and correlation times for stationary receivers of a few minutes. Receiver measurement noise is predominantly high frequency and has a standard deviation between 0.2 m and 1.5 m depending on receiver technology [28]. Such errors will be discussed in Section 3.1.

3.1 GPS Errors and combinations to correct them

The code pseudorange[1] is defined by measures $P1$ (or C/A) and $P2$, between a receiver i and a satellite j [52]. These signals can be represented as:

[1]Pseudorange or apparent distance between the satellite and the receiver, obtained through the correlation of the modulated code in the received signal from the satellite with the replica generated in the receiver, $P = c\triangle T$, is affected by a series of terms which are added to the geometric distance.

$$
\begin{aligned}
P1_i^j &= \rho_i^j + c\left(dt_i - dt^j\right) + rel_i^j + T_i^j + \alpha_1 I_i^j + K1_i^j + M_{P_1,i}^j + \varepsilon_{P_1,i}^j \\
P2_i^j &= \rho_i^j + c\left(dt_i - dt^j\right) + rel_i^j + T_i^j + \alpha_1 I_i^j + K2_i^j + M_{P_2,i}^j + \varepsilon_{P_2,i}^j
\end{aligned}
$$

Where:

Geometric distance [ρ_i^j]: It corresponds to the Euclidean distance between satellite position at emission epoch and the receiver at the moment of the signal reception.

Offsets of receiver clock [dt_i] and satellite clock [dt^j]: They correspond to the clock synchronism errors referring to GPS time scale.

- The offset of the receiver clock $[dt_i]$ is estimated at the same time as its coordinates.
- The offset of the satellite clocks $[dt^j]$ can be calculated from the navigation message,

Relativistic correction [rel_i^j]: The rate of advance of two identical clocks, placed one in the satellite and the other on the terrestrial surface, will differ due to the difference of the gravitational potential (general relativity) and to the relative speed between them (special relativity).

Tropospheric delay [T_i^j]: the troposphere is the lower part of the atmosphere where most weather phenomena take place. The signal propagation in this region will be affected by the specific atmospheric conditions (e.g. temperature, humidity. . .) and will result in range measurement errors. The size of the error will also depend on the satellite elevation above the horizon.

Ionospheric delay [αI_i^j]: The Ionosphere is an ionized layer of the atmosphere located a few hundred kilometres above the surface of the Earth. When transiting through the ionosphere, the satellite navigation signals propagation is disturbed and range measurement errors result. The size of the error will depend on the level of solar activity (following approximately an 11-year cycle) (see Figure 3.1) and the satellite elevation above the horizon.

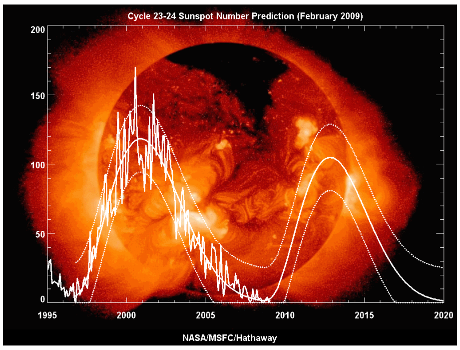


Figure 3.1: Sunspot number observed and predicted from 1995 to now [12]

Instrumental delays [K_i^j]: Possible sources of these delays are antennas, cables, as well as different filters used in receivers and satellites.

Multipath [$M_{P_1,i}^j$]: The interference by multipath is generated when a signal arrives, by different ways, at the antenna. Its principal cause is the antenna closeness to the reflecting structures, and it is important when the signal comes from the satellite with low elevation.

Noise [$\varepsilon_{P_1,i}^j$]: In this term, the measurement noise of pseudorange is included and all non previously modelled effects.

The contribution of these errors to the pseudorange is exemplified in Figure 3.2,

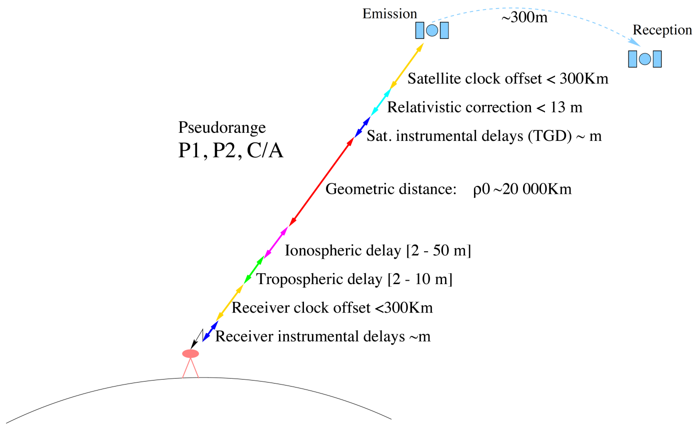


Figure 3.2: Errors magnitude in pseudorange [1]

The main part of the signals that the receivers need in order to get the position is the geometric distance [ρ_i^j]. This is the parameter that contains the exact distance from the receiver to the satellite, so the next step is to correct all the errors described above.

Apparent distance between satellite and receiver can also be measured from the carrier signal phase, obtaining in this case:

$$L_i^j = \rho_i^j + c\left(dt_i - dt^j\right) + rel_i^j + T_i^j - \alpha_1 I_i^j + B_i^j + w_L + m_{L,i}^j + \varepsilon_{L,i}^j$$

Where:

Wind-up [w_L]: Is the term due to signal polarization.

Ambiguity phase [B_i^j]: Is an ambiguity phase term owing to the signal acquisition, an ambiguity of an integer number of wavelengths ($N\lambda$) appears to which one has to add instrumental constants k_i, k_j from satellite and receiver, respectively ($B_i^j = k_i + k_j + \lambda N_i^j$).

As mentioned in page 51, the errors can be classified as common mode errors or non-common mode errors. The first group is referred to the errors that follows the same pattern (or similar) for the receivers located in the same region. With this, if a common mode error can be corrected by a receiver (or station), the rest of the receivers could easily correct it with the information given by the "corrector". This is one of the principles of working of some GPS Augmentation Systems such as GBAS[2] or SBAS[3]. The errors are classified as [52]:

- *Common mode errors:*
  - Dispersive ionospheric error [αI_i^j]
  - Non-dispersive atmospheric errors [T_i^j]
  - Satellite clock bias [dt^j]
  - Ephemeris error [$E(t)$]
  - Relativistic errors [rel_i^j]
- *Non-common mode errors:*
  - Offset of the receiver clock [dt_i]
  - Multipath error [$M_{P_1,i}^j$]
  - Instrumental delays error [K_i^j]
  - Wind-up [w_L]

[2]GBAS: Ground-Based Augmentation System (see page 58)
[3]SBAS: Satellite-Based Augmentation System (see page 65)

– Ambiguity phase [B_i^j]
– Random measurement noise [$\varepsilon_{P_1,i}^j$]

Some of these errors can be corrected by the GPS receiver only by the combinations of the observables P1, P2, L1 and L2 [1]. The problem of these combinations (modelling) is that the receiver has to be able to detect both frequencies, which is only able for military or authorised users. Nevertheless, some civil-user receivers companies have implemented several tricky strategies to achieve an error correction acceptable taking into account the limitations of the receivers. The observables are:

$$\begin{aligned}
& Codes\,(Pseudoranges) \\
P1_i^j &= \rho_i^j + c\left(dt_i - dt^j\right) + rel_i^j + T_i^j + \alpha_1 I_i^j + K1_i^j + M_{P_1,i}^j + \varepsilon_{P_1,i}^j \\
P2_i^j &= \rho_i^j + c\left(dt_i - dt^j\right) + rel_i^j + T_i^j + \alpha_1 I_i^j + K2_i^j + M_{P_2,i}^j + \varepsilon_{P_2,i}^j
\end{aligned}$$

$$\begin{aligned}
& Phases\,(Carries\,phases) \\
L1_i^j &= \rho_i^j + c\left(dt_i - dt^j\right) + rel_i^j + T_i^j - \alpha_1 I_i^j + B1_i^j + w_{L_1} + m_{L_1,i}^j + \varepsilon_{L_1,i}^j \\
L2_i^j &= \rho_i^j + c\left(dt_i - dt^j\right) + rel_i^j + T_i^j - \alpha_2 I_i^j + B2_i^j + w_{L_2} + m_{L_2,i}^j + \varepsilon_{L_2,i}^j
\end{aligned}$$

There are four important combinations that has to be explained depending on which of the error parameter is going to be corrected, or depending on the information that is going to be used to accurate de distance between the satellite and the receiver.

- *Ionospheric free combination:*

  As the ionospheric effect depend on the square of the frequency ($\alpha_i = {}^{40.3}/_{f_i^2}$), this term can be easily cancelled by these combinations:

$$PC = \frac{f_1^2 P1 - f_2^2 P2}{f_1^2 - f_2^2} \quad ; \quad LC = \frac{f_1^2 L1 - f_2^2 L2}{f_1^2 - f_2^2}$$

  The result of the combinations is a major accuracy in the determination of the distance due to the cancellation of the ionospheric error term. Solving the equations, the result obtained is:

$$\begin{aligned}
PC &= \rho + c\left(dt_i - dt^j\right) + rel + T + KC + M_{PC} + \varepsilon_{PC} \\
LC &= \rho + c\left(dt_i - dt^j\right) + rel + T + BC + w_{LC} + m_{LC} + \varepsilon_{LC}
\end{aligned}$$

- *Narrow lane* (PW) *and wide-lane* (LW) *combinations:*

  LW combination gives an observable with a wavelength λW = 86.2 cm, four times bigger than $L1$ or $L2$, which makes it very useful for (cycle-slips) detections. To do so, Melbourne-Wübbena combination is used ($W = LW - PW$).

$$PW = \frac{f_1 P1 + f_2 P2}{f_1 + f_2} \quad ; \quad LW = \frac{f_1 L1 - f_2 L2}{f_1 - f_2}$$

  Solving the equations one can see that the result is that the α_W term is $\alpha_W = {}^{40.3}/_{f_1 f_2}$, making easy the detection of cycle-slips. As a result, the distance accuracy increases.

$$\begin{aligned} PW &= \rho + c\left(dt_i - dt^j\right) + rel + T + \alpha_W I + KW + M_{PW} + \varepsilon_{PW} \\ LW &= \rho + c\left(dt_i - dt^j\right) + rel + T - \alpha_W I + BW + m_{LW} + \varepsilon_{LW} \end{aligned}$$

- *Ionospheric combination:*

  It cancels the geometric part of the measurement, leaving the ionospheric effect and the instrumental constants (besides multipath and observational noise). It is also used to detect cycle-slips in the phase.

$$PI = P2 - P1 \quad ; \quad LI = L1 - L2$$

  In these combinations the distance is cancelled, so the remaining terms enable an easily detection of the cycle-slips in the phase.

$$\begin{aligned} PI &= \alpha_I I + KI + M_{PI} + \varepsilon_{PI} \\ LI &= \alpha_I I + BI + w_{LI} + m_{LI} + \varepsilon_{LI} \end{aligned}$$

Apart from these combinations implemented in the GPS receivers, there are several ways to improve the accuracy in positioning. Next chapter focus on the main techniques to improve the accuracy using external information.

Chapter 4

Techniques to improve GPS accuracy

The GPS system is the most widely used positioning system worldwide, largely because its performance has been uninterrupted for decades, unlike the GLONASS system, giving the user confidence that the system will be operational when needed. The fact that the service offered to civilian users is free, added to the deactivation of the S/A in 2000, has made the marketing of GPS receivers has been a success. Nowadays, practically the majority of the cars are equipped with a GPS (either integrated or not), many mobile phones incorporate GPS in its functions, there are cars or people locators based on GPS, in aviation and marine navigation instruments are equipped with GPS receivers, etc. These are a few examples of how important is GPS in our technological society.

However, despite the fact that GPS currently uses are much broader than a decade ago, the operating principle of many GPS receivers are still based on the same principles as 20 years ago. New generations of GPS satellites are introducing new signals to provide an improvement in the accuracy of civilian users (see Section 2.1.1.1), but many receivers still do not using them. The fact of need an improvement in accuracy or just to get a quick positioning at any given time, has promoted the development of techniques called *GPS Augmentation systems*. The main purpose of these methods are to enhance the performance of the current GNSS with additional information to:

- Improve *integrity* via real-time monitoring
- Improve *accuracy* via differential corrections
- Improve *availability* and *continuity*

These techniques are based on the use of external information from the GPS signal to help the position calculation. Information can be received in different ways, Radio Frequency (UHF, VHF, etc.); satellite signals (SBAS); data packages via UMTS, etc. As a result, depending on the technique used, the GPS receivers must have a new receiver module to detect such signals, in order to use them in the positioning equations or error correction algorisms.

4.1 Differential GPS (DGPS)

DGPS (Differential GPS) [13] is a particular case of GBAS (Ground Based Augmentation System) based on the use of the accurate location of a fixed point (receiver) to correct the errors of the GPS receivers. GBAS commonly consist of one or several ground stations, with a precise position known, which receive GPS data from the GNSS. Once the signal has been corrected, the information is transmitted by radio directly to the GPS users. GBAS System differs from SBAS mainly in that it is not designed to provide service over large geographic regions, due to the fact that the broadcasted signal from the stations is useful in less than 150 km from the base. That is why its main use is given in air traffic control to support precision approach phases, where base stations are located near the airport area. Although that, the use is becoming wider in other fields.

DGPS was originally initiated by the U.S. Coast Guard to counter the accuracy degradation caused by S/A. Even with S/A eliminated, DGPS continues to be a key tool for highly precise navigation on land and sea. DGPS can yield measurements accurate from some centimetres to a couple of meters in stationary situations (in moving applications the accuracy is about 1-2 meters). Differential GPS involves the co-operation of two receivers, one that's stationary and another that's roving around making position measurements. The accuracy will be closely related with the distance between GPS receivers and the Base Station.

As each GPS receivers use timing signals from at least four satellites to establish a position then each of those timing signals is going to have some error or delay depending on what sort of problems have occurred it on its journey down to Earth as mentioned in section 3.1. Since each of the timing signals that go into a position calculation has some error, that calculation is going to be a compounding of those errors (Dispersive ionospheric error, satellite clock drift, tropospheric error, etc.) [53].

However if two receivers are fairly close to each other, say within a few hundred kilometres, the signals that reach both of them will have travelled through virtually the same slice of atmosphere, and so will have virtually the same errors. This means that one of these receivers can measure the timing errors and then provide correction information to the other receivers that are roving around. This allows virtually all errors to be eliminated from the system. The error correction will be better or worse depending on the distance between the rover and the reference. A survey made in 1993 stated that estimated error growth of 0.67 m per 100 km from the broadcast site but more recent measurements of accuracy across the Atlantic, in Portugal suggest a degradation of just 0.22 m per 100 km [54].

The reference station operates by receiving the same GPS signals as the roving receiver but instead of working like a normal GPS receiver it uses its known position to calculate timing, rather than using timing signals to calculate position. Essentially determining what the travel time of the GPS signals should be, and compares it with what they actually are. The difference is an "error correction" factor. The receiver then transmits this error information to the roving receiver so it can use it to correct its measurements.

Since the reference receiver has no way of knowing which of the many available satellites a roving receiver might be using to calculate its position, the reference receiver quickly runs through all the visible satellites and computes each of their errors. Then it encodes this information into a standard format and transmits it to the roving receivers. The roving receivers can then apply the corrections for particular satellites they are using (see Figure 4.1 [55]).

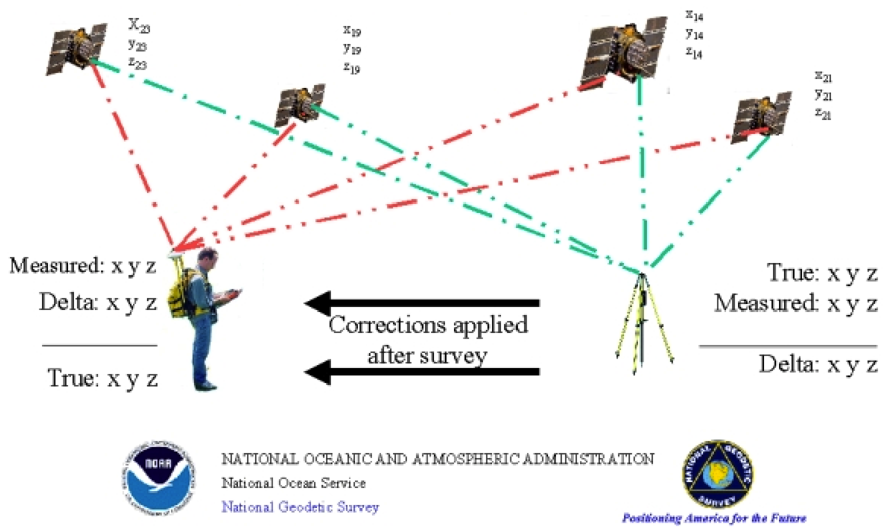


Figure 4.1: DGPS Schematic Diagram [13]

There are also different kinds of DGPS, for use when users do not need precise positioning immediately. This is termed Post Processing DGPS, and is used when the roving receiver just needs to record all of its measured positions and the exact time it made each measurement. Then later, this data can be merged with corrections recorded at a reference receiver for a final clean-up of the data, meaning you don't need the radio link required in real-time systems. Another form of DGPS, called Inverted DGPS, which is used to save money when operating a large fleet of users. With an inverted DGPS system the users would be equipped with standard GPS receivers and a transmitter, and would transmit their standard GPS positions back to the tracking station (the main office). Then at the tracking station the corrections would be applied to the received positions.

Maybe one of the most important types of DGPS is the one based on Real-Time Kinematic (RTK DGPS). In standard DGPS technology, only corrections to pseudoranges based on the Navigation Message are being transmitted, which brings rover positional common mode errors down to values about 1m. The remaining DGPS error source is mainly multipath, which can be reduced by the use of special multipath mitigation methods. High-precision navigation/surveying applications require RTK (Real-Time Kinematic) technology, which is based on the use of carrier phase. Carrier phase measurements are extremely precise (down to the fractions of millimetre), but they contain an unknown integer initialization constant, the so-called "phase ambiguity". Therefore RTK positioning has to resolve integer ambiguities to achieve the high level of precision. In practice, RTK systems use a single base station receiver and a number of mobile units. The base station re-broadcasts the phase of the carrier that it measured, and the mobile units compare their own phase measurements with the ones received from the base station. There are several ways to transmit a correction signal from base station to mobile station. The most popular way to achieve real-time, low-cost signal transmission is to use a radio modem, typically in the UHF band (see Figure 4.2 [55]).

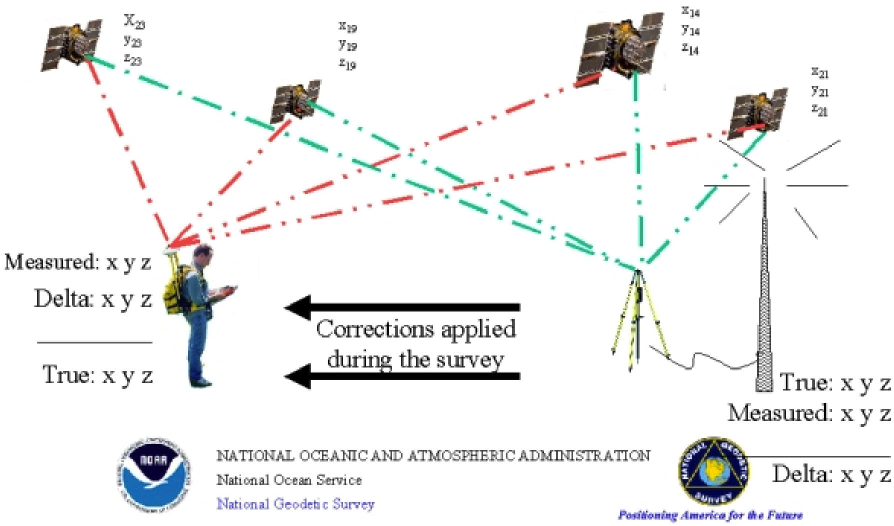


Figure 4.2: RTK Schematic diagram [13]

The base station of the RTK technology is normally not further than 20 km from the receiver in order to guarantee a centimetre accuracy to the user. These receivers are also the only system that can achieve complete repeatability, consequently, the cost of that technology is really expensive compared to other positioning systems. In addition, it has to be noticed that, nowadays, standard DGPS needs an investment of around 30.000 € to install a Reference Base [53], which is also an expensive method. The problem of these expensive technologies is what drove a group of researchers from University of Blaise Pascal Clermont-Ferrand II (France) to develop a method called LCD-GPS (Low Cost Differential GPS and also Local Cooperative Differential GPS). This solution consists of a set of low cost standard civil GPS communicating receivers, part of them used in fixed manner as base stations and the other part is used as mobiles. All base stations have their position coordinates known with a good accuracy. They analyse continuously the instantaneous GPS errors and cooperate together to deduce a global error correction. This correction is sent wirelessly and has to be applied to mobile node positions (or fixed nodes which are not part of base stations) in order to improve their position accuracy [53]. The use of cheap prototypes to build the receivers and the base stations is what has allowed to reduce the cost of this technology.

Nowadays, there are several companies that offer DGPS service all around the world. The National Geodetic Survey (NGS), an office of NOAA (National Oceanic and Atmospheric Administration) [56], coordinates a network of Continuously Operating Reference Stations (CORS). In Europe, there are some countries that have supported this technology, mostly the counties with large part of coast in order to improve the safety in the sea. Northern countries, as well as U.K., France and Spain, are the countries with more maritime stations (see Figure 4.3), the majority of them, following the recommendations of the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) [57]. Nowadays, apart from the stations situated on the coast, there are a great number of them also in land, the majority of them implemented by private companies. Figure 4.3 shows the location of the stations around the world and in Europe (with the coast and land stations).

Australia, Russia and some Asian countries also count with a DGPS infrastructure [14, 58].

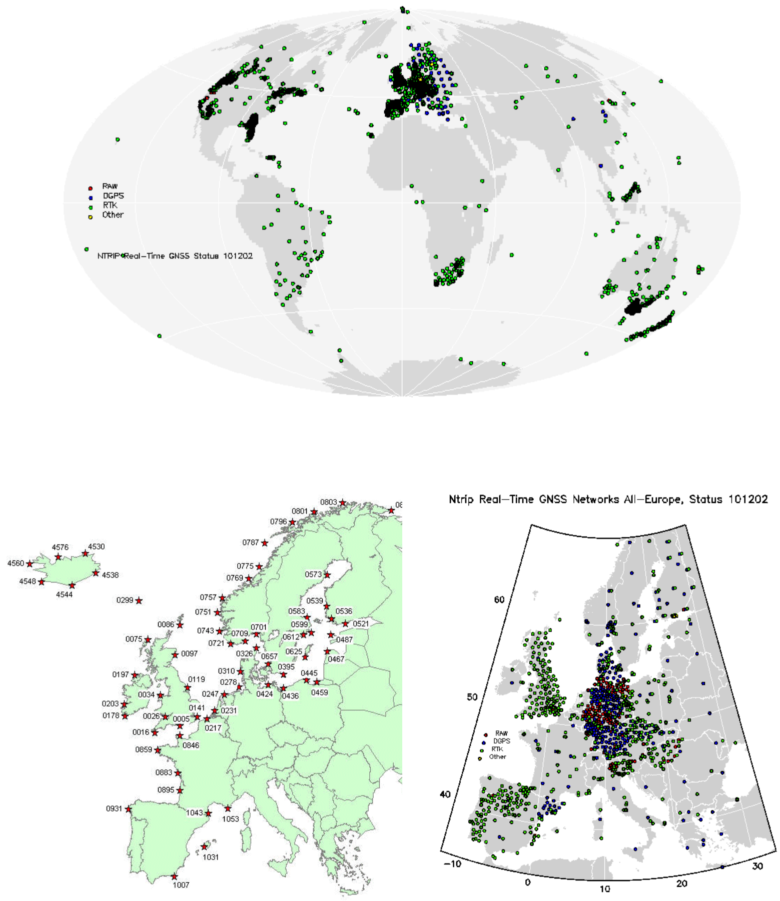


Figure 4.3: DGPS Stations Coverage

In Poland there are also DGPS coverage. Established since 1995 and following the IALA R-NAV Recommendations, DGPS-PL was implemented in the northern coast of Poland and has been modernised in 2007/2008 in order to provide Safety of Navigation in the Baltic Sea Area. This system is formed by two DGPS Stations called *Dziwnów* and *Rozewie* (see Table 4.1 and Figure 4.4 and), although 2 additional Integrity Monitor stations are planned.

Table 4.1: *Dziwnów* and *Rozewie* Stations

Table of DGNSS Stations			Country: Poland		Date of last amendment: July 2008			
Station Name	Identification Nos Reference Station(s)	Identification Nos Transmitting Station	Geographic Position Lat/Lon	Station in operation	Integrity Monitoring	Transmitted Message types	Freq (kHz)	Bit-rate (bps)
Dziwnów	741/742	481	54º01' N/14º44' E	yes	yes	9,3,7,16	283,5	100
Rozewie	743/744	482	54º49' N/18º20' E	yes	yes	9,3,7,16	301,0	100

Figure 4.4: *Dziwnów* and *Rozewie* Stations [14]

Regarding the DGPS receivers, there are several manufacturers that have implemented receivers for this technology (i.e. Leica Geosystems AG, Magellan Navigation, Septentrio NV, Topcon Europe Positioning, Trimble, AD Navigation AS, Fugro, Hemisphere GPS or C&C Technologies). Some of them are able to detect and combine both Galileo and GPS signals and their accuracy can be up to 10mm+1ppm for horizontal measurements and 15mm+1ppm for vertical measurements (with Differential/RTK). In case of RTK static measurements, one of the best DGPS receivers[1] accurate the position up to 5mm+0.5mm and 10mm+1.0mm in kinematic (Horizontal). According to the survey from *Hydro International* the DGPS Receiver with an affordable RTK solution (less than 10,000 $) and with a centimetre accuracy is made by C&C Technologies C-Nav2050 [59]. Figure 4.5 shows two types of DGPS receivers.

(a) C&C Technologies C-Nav2050

(b) Trimble DSM 232 DGPS Receiver

Figura 4.5: DGPS Receivers

[1] Leica Geosystems AG, Model Leica GX1230 GG

4.2 Satellite-Based Augmentation System (SBAS)

One of the limitations of DGPS is the degradation of the accuracy when the receiver is moving away from the DGPS Base Station. Furthermore, the area covered by one station is about 150 km of radius, so a large amount of stations are needed in order to guarantee a determined level of accuracy in a large area. Considering these limitations, in 1993 the U.S. Army implemented a system based on SBAS (Satellite-Based Augmentation System). SBAS Systems are designed to augment the Navigation System constellation by broadcasting additional signals from geostationary (GEO) satellites and providing differential correction messages and integrity data for the satellites that are in the view of a monitoring station network. This increases the accuracy and the confidence a user can have in the satellite navigation positioning solution extending the field for satellite navigation to support more demanding applications [15].

SBAS has the ability to support navigation in all phases of flight from en route navigation to vertically guided approach procedures with a Decision Height as low as 61 m above runway threshold, in other words procedures that are essentially equivalent to Precision Approach Category I (Categories defined by ICAO, http://www.icao.int/). This type of vertically guided approach procedure is known as Localizer Performance approach with Vertical guidance (LPV). SBAS is able to achieve the level of performance required for vertically guided approach procedures because: - it performs a real-time monitoring of all GPS satellites in view (and its own GEOs) as well as a real-time monitoring of the signal propagation delays caused by the ionosphere in the region of the main service area. - it broadcasts satellite and ionospheric corrections and associated integrity information, which the SBAS User Equipment (UE) uses to improve the navigation solution and compute sufficiently small integrity bounds for the navigation solution [60].

Five SBAS implementations are currently operational or in phase of developement: the Wide Area Augmentation System (WAAS) from the US; the European Geostationary Navigation Overlay System (EGNOS) from the EU; the Russian Wide Area Augmentation System (SDCM), which is currently in an early stage of developmentand, from the Russian Federation; the MTSAT Satellite Augmentation System (MSAS) from Japan; and the GPS-Aided and GEO-Augmented Navigation System (GAGAN) from India, which is in a later stage of development. Figure 4.6 shows the distribution of these augmentation systems.

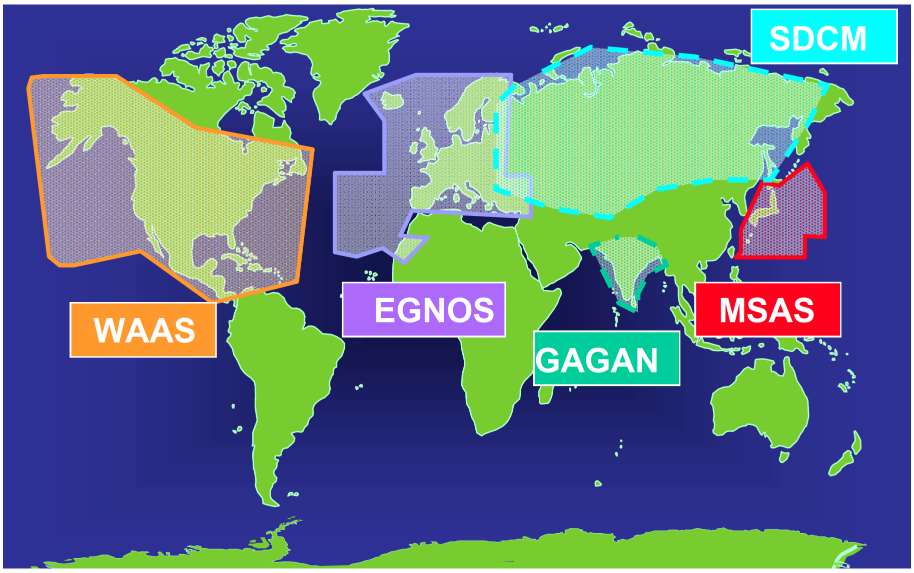


Figure 4.6: Distribution of the different SBAS [15]

All these SBAS implementations follow the same (or almost the same) structure. SBAS is composed by (see Figure 4.7):

- Ground reference stations
- One or more Master Stations
- One or more satellite uplink stations
- One or more geostationary earth orbiting satellites (GEOs)
- Communication network linking the various ground components

The reference stations continuously collect ranging and information data from all GPS satellites in view and transmit that information to the master stations. Using that information as well as the surveyed positions of reference station receiving antennas, the master stations compute corrections and integrity information, format the information in a set of pre-defined messages, and transmit that information to the uplink stations. The uplink stations modulate the messages on uplink signals and transmit these signals to navigation payloads on the GEOs. The navigation payloads then broadcast the augmentation signals (at the GPS L1 frequency) to the users. The uplink stations also drives the timing of the GEO augmentation signals to allow those signals to be used as additional ranging sources. Redundancy is typically built throughout the entire system (reference receivers, master stations, communication network, uplink stations and GEOs) in order to achieve a high continuity performance as well as high system reliability [60].

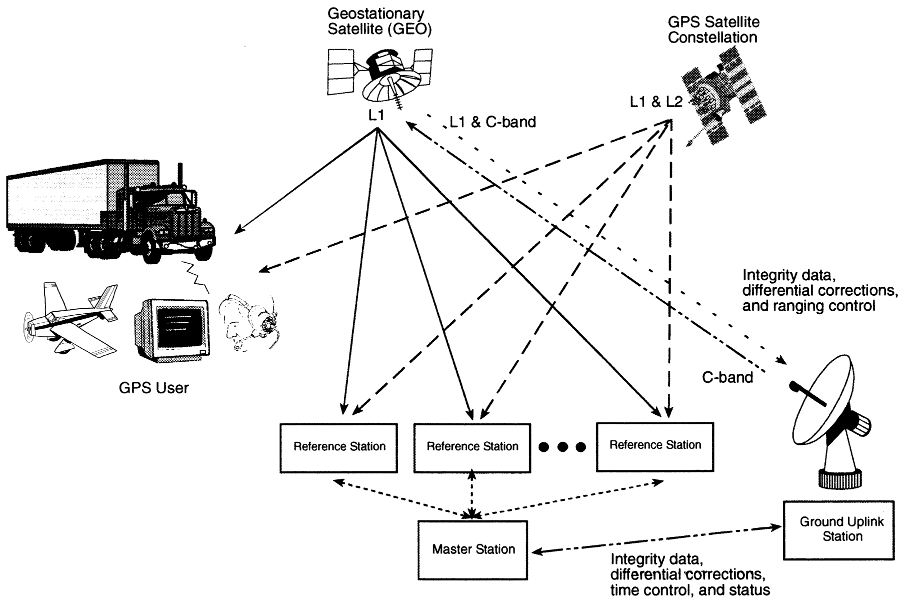


Figure 4.7: SBAS elements

The performance of an augmented GPS approach and landing system is evaluated by the metrics [61, 62]:

- *Accuracy*, defined to be the 95% (or 2σ) bound on the total Navigation System Error (NSE) under nominal (or fault-free) conditions. The NSE is the difference between the true position of the user and the position reported by its navigation sensors.

- *Integrity*, a measure of the capability of the navigation system to detect a fault. Technically, integrity is specified by the probability that a hazardous condition goes unreported by the navigation system.

- *Continuity*, is the ability of the total system (comprising all elements necessary to maintain aircraft position within the defined airspace) to perform its function without interruption during the intended operation. More specifically, continuity is the probability that the specified system performance will be maintained for the duration of a phase of operation, presuming that the system was available at the beginning of that phase of operation.

- *Availability*, a measure of how often the navigation system is available for use and is defined to be the percentage of time that the accuracy, integrity, and continuity requirements are met.

- *Service volume size*, defined to be the geographic area over which an augmented GPS navigation system's accuracy, integrity, continuity, and availability functions are guaranteed to be within some specified requirements.

Although all the SBAS Systems are based in the same principle, each different SBAS implementation have its own particularity. Now is going to be described the WAAS and EGNOS systems in order to give the reader a global idea of their characteristics.

4.2.1 Wide Area Augmentation System (WAAS)

WAAS is the FAA's SBAS that was commissioned in 2003. It now provides continuous horizontal navigation throughout the National Airspace System (NAS). In addition, it provides vertical guidance to most of the Coterminous United States (CONUS[2]) greater than 99% of the time [62]. WAAS provides extended coverage both inland and offshore compared to the land-based DGPS (differential GPS) system. Another benefit of WAAS is that it does not require additional receiving equipment, while DGPS does. WAAS is intended to enable aircraft to rely on GPS for all phases of flight, including precision approaches to any airport within its coverage area. Figure 4.8 graphically shows the accuracy improvement in GPS since the S/A on until the use of WAAS.

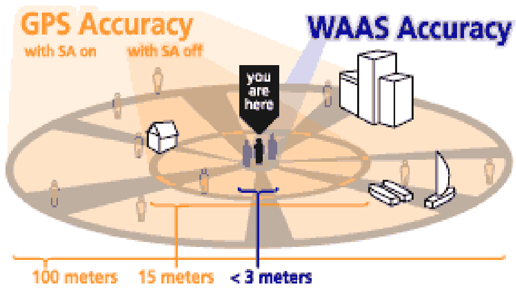


Figure 4.8: Accuracy improvement with WAAS

WAAS supports three types of approach procedures with vertical guidance [63, 64]:

- LNAV/VNAV (Lateral Navigation / Vertical Navigation) approaches use lateral guidance (556m lateral limit) from GPS and/or WAAS and vertical guidance provided by either the barometric altimeter or WAAS. Aircraft that don't use WAAS for the vertical guidance portion must have VNAV-capable altimeters, which are typically part of a flight management system (FMS). FMS avionics are more expensive than WAAS receivers. When the pilot flies an LNAV/VNAV approach lateral and vertical guidance is provided to fly a controlled descent, a safer manoeuvre, to the runway. The decision altitudes on these approaches are usually 350 feet above the runway.

[2]The contiguous United States are the 48 U.S. states on the continent of North America that are south of Canada, plus the District of Columbia. The term excludes the states of Alaska and Hawaii, and all off-shore U.S. territories and possessions.

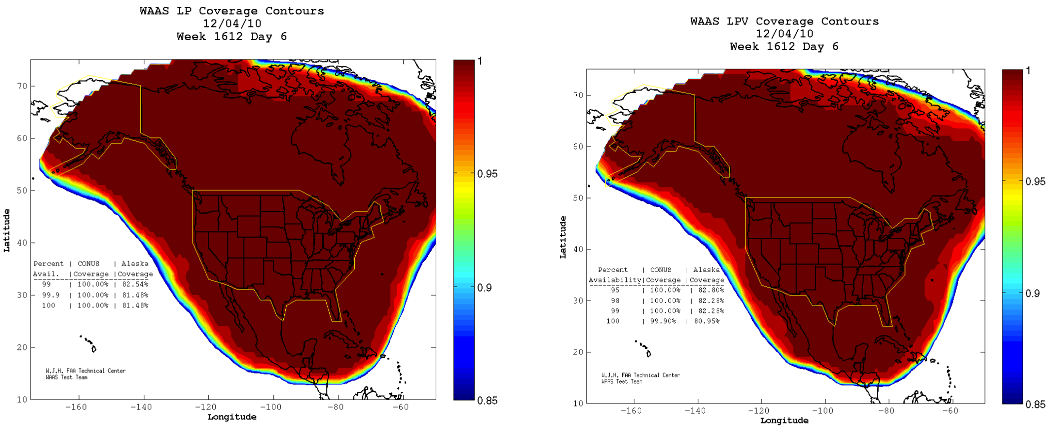
- LPV, a WAAS operational service level with a HAL[3] equal to 40 meters and a VAL[4] equal to 50 meters [62]. LPV is similar to LNAV/VNAV except it is much more precise (40m lateral limit), enables descent to 200-250 feet above the runway, and can only be flown with a WAAS receiver. LPV approaches are operationally equivalent to the legacy instrument landing systems (ILS) but are more economical because no navigation infrastructure has to be installed at the runway.

- LP (Localizer Performance) is a NPA procedure that uses the high precision of LPV for lateral guidance and barometric altimeter for vertical guidance. These approaches are needed at runways where due to obstacles or other infrastructure limitations, a vertically guided approach (LPV or LNAV/VNAV) can not be published. LP approaches can only be flown by aircraft equipped with WAAS receivers. The minimum descent altitude for the LP approach is expected to be approximately 300 feet above the runway.

Figure 4.9 shows the area service and the availability of LP and LPV approaches. Note that in CONUS, the LP service is available the 100% of the time in the 100% of the service area (see Figure 4.9a), whereas the availability of the LPV is lower (see Figure 4.9b). There is another service derived from the LPV called LPV200, which specifies lower values of HAL and VAL. Consequently, the service volume size with a large availability is smaller that the other cases [16].

[3]The Horizontal Alert Limit (HAL) is the radius of a circle in the horizontal plane (the local plane tangent to the WGS-84 ellipsoid), with its centre being at the true position, which describes the region that is required to contain the indicated horizontal position with a probability of $1 \cdot 10^{-7}$ per flight hour, for a particular navigation mode, assuming the probability of a GPS satellite integrity failure being included in the position solution is less than or equal to 10^{-4} per hour.

[4]The Vertical Alert Limit is half the length of a segment on the vertical axis (perpendicular to the horizontal plane of WGS-84 ellipsoid), with its centre being at the true position, which describes the region that is required to contain the indicated vertical position with a probability of $1 \cdot 10^{-7}$ per flight hour, for a particular navigation mode, assuming the probability of a GPS satellite integrity failure being included in the position solution is less than or equal to 10^{-4} per hour.



(a) WAAS LP Coverage Contours (b) WAAS LPV Coverage Contours

Figura 4.9: WAAS Coverage [16]

WAAS is composed by three segments:

- Ground Segment
- Space Segment
- User Segment

4.2.1.1 Ground Segment

The principal functions of the ground segment are to monitor the status of the GPS SVs, to process the data in order to correct the errors of the signals and to upload the data to the WAAS GEOs.

The Ground Segment is composed by (see Figure 4.10):

- Wide-Area Reference Stations
- Wide-Area Master(s) Station(s)
- Wide-Area Ground Uplink Station

The Reference Stations are located at precisely surveyed locations in the U.S. territory and are in charge of monitor the status of the SVs. Each has three dual frequency GPS receivers that can be used to crosscheck the measurements. By taking measurements from two frequencies, the propagation delay caused by the signal passing through the ionosphere can be separated from the other error sources. The information is then transmitted to the Master Station, which performs the necessary corrections that has to be transmitted to the GEOs. WAAS sends corrections for the ionospheric delay as well as for the GPS satellites' clock and orbital errors. Each correction is sent to the user at least every five minutes. Because the reference stations know their location to within centimetres, they can determine what errors may be present on the ranging signals from the satellites. These errors are isolated to their individual components for efficient broadcast. One of the best enhancements of the WAAS System is that performs an estimation of the Ionospheric delay throughout the coverage area based on the delays calculated for each reference station, therefore, the receivers have a very good error correction regardless of location. Two primary types of messages are generated by the Master Station: integrity, and range corrections.

Integrity messages are used to indicate which satellites are functioning within acceptable tolerances. Range corrections are parameters that permit the estimation of ionospheric delays, and satellite clock and ephemeris errors. All the data from the Master Station is transmitted by the ground network to the Ground Antennas, which broadcast the data to the WAAS GEOs [63].

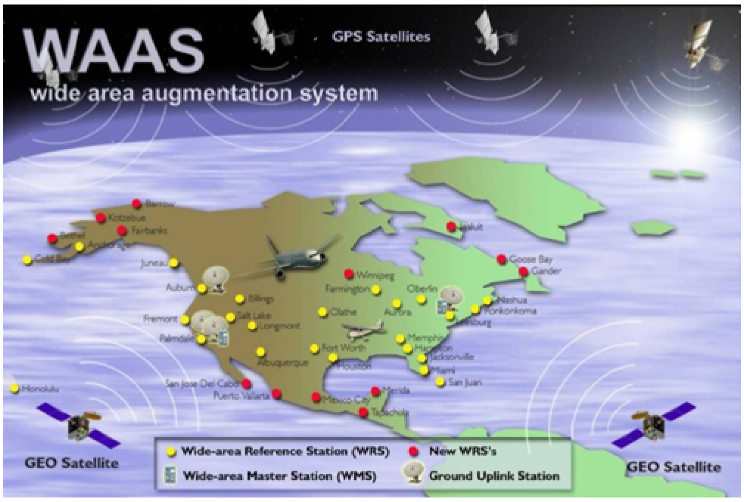


Figure 4.10: WAAS architecture

4.2.1.2 Space Segment

The Space segment is composed by the Geostationary Earth Orbit (GEO) satellites, which are located in fixed orbital positions over the equator. The GEO satellites broadcast the messages on L1 frequency for use by WAAS receivers. The WAAS GEO satellites may also serve as additional sources of navigation ranging signals, thereby increasing the number of usable "GPS-like" satellites.

There are three satellites broadcasting in the WAAS Coverage area. Figure 4.11 shows the area covered by each satellite.

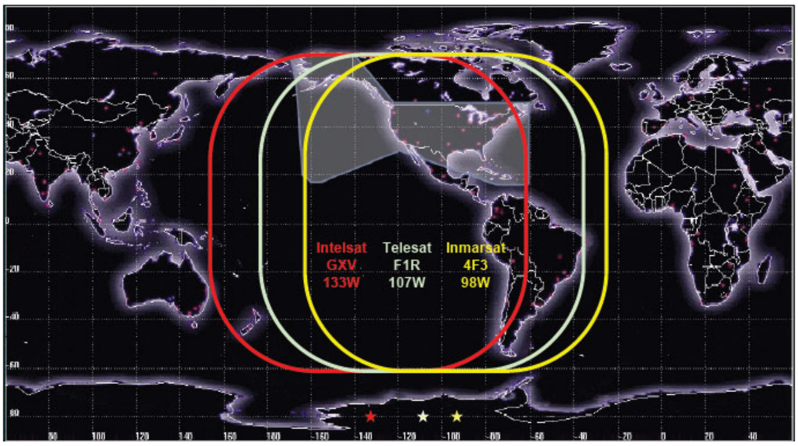


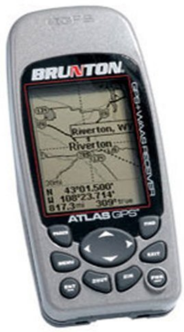
Figure 4.11: WAAS GEOs and coverage area [17]

4.2.1.3 User Segment

User segment is referred to the equipment of the end user to detect the GPS and WAAS signals. The receivers must determine its location using the GPS signal received by the satellites and correct the pseudoranges with the messages from the GEOs WAAS satellites. Firstly, the receiver calculates the position by the fast type correction data (corrected satellite position and clock data), with this, the receiver can begin to use the slow corrections to accurate the location. The slow type correction data includes the ionospheric delay.

There is a large variety of WAAS receivers. The next generation of the GPS with WAAS receivers is going to be implemented by NovAtel thanks to the three-year contract with the FAA worth up to US$9.7 million [65]. Figure 4.12 shows two examples of GPS/WAAS receivers. Furuno GP32 GPS/WAAS receiver and Brunton Atlas GPS/WAAS.

(a) Furuno GP32 GPS/WAAS receiver



(b) Brunton Atlas GPS/WAAS receiver

Figura 4.12: GPS/WAAS receivers

4.2.2 European Geostationary Navigation Overlay Service (EGNOS)

The European Geostationary Navigation Overlay Service (EGNOS) [18] is a SBAS under development by the European Space Agency (ESA), the European Commission and EUROCONTROL. It is intended to supplement the GPS, GLONASS and Galileo systems by reporting on the reliability and accuracy of the signals. by providing differential corrections to improve positioning accuracy and signal quality measurements to provide integrity to satellite navigation users in Europe [66].

Unlike WAAS, EGNOS can readily be used in a wide range of domains. As stated in the previous section, WAAS is clearly focused on improving navigation and positioning for the air service, which implies that many areas are not fully benefiting from the augmentation system. The main domains where EGNOS will be beneficial are:

- *Road navigation*

  Accuracy, as well as integrity and availability are improved by EGNOS, consequently a better *fleet tracking* is possible. With this, transport companies and users of these services are benefit.

- *Aeronautics*

  Air transport is becoming more and more important. EGNOS is designed to assist navigation both en-route as well as during landing, which will benefit the aerospace community.

- *Maritime*

  Complementing EGNOS with the services already provided by marine radio beacons, maritime navigation will be safer.

- *Agriculture*

  Due to the high positioning accuracy EGNOS provides and in combination with geodetic techniques an improvement in the area of property boundary mapping, land parcel identification and geo-traceability. Furthermore, this augmentation method enables the high-precision spraying of fertilisers and pesticides, reducing the amount of chemicals needed for achieving optimal yield and productivity. It can also support innovative applications such as automatic tractor guidance or remote livestock positioning and supervision.

- *Personal navigation applications*

  EGNOS opens a wide range of new possibilities in applications such as guiding aids for the blind, emergency localisation, friend finding or geo-localised advertising.

- *Clock synchronising*

  EGNOS broadcasts a reliable time standard with unprecedented accuracy for use by computer and telecommunication networks.

EGNOS will offer when fully operational three types of service [15]:

- The Open Service (OS), freely available to the public in Europe. The main objective of the EGNOS OS is to improve the achievable positioning accuracy thanks to the correction of several error sources affecting the GPS signals. The minimum horizontal accuracy[5] is 3m horizontal, whereas the vertical accuracy[6] is 4m.

- The Safety of Life Service (SoL), that will provide the most stringent level of signal-in-space performance to all Safety of Life user communities in Europe. The main objective of the EGNOS SoL service is to support Civil Aviation applications up to LPV (Localizer Performance with Vertical guidance) operations.

- The Commercial Data Distribution Service (CDDS) for customers who require enhanced performance for commercial and professional use. EGNOS CDDS provides authorised customers all EGNOS augmentation messages in real time (including satellite clocks and ephemeris corrections, propagation corrections and integrity information in the SBAS format) and raw data from the Ranging and Integrity Monitoring Stations (RIMSs) in real time (including satellite high precision pseudorange measurements).

Regarding the EGNOS architecture, it is similar to WAAS, with ground, space and user segments.

4.2.2.1 EGNOS Architecture

Ground Segment

The Ground Segment is in charge of monitor the SVs, calculate error corrections and upload the GPS-like signals with the information to the EGNOS Satellites. The GS is composed by 34 Ranging and Integrity Monitoring Stations (RIMS), 4 Mission Control Centres (MCC), 6 Navigation Land Earth Stations (NLES) and the EGNOS Wide Area Network (EWAN). Two additional facilities are also deployed as part of the GS to support system operations and service provision, namely the Performance Assessment and Checkout Facility (PACF) and the Application Specific Qualification Facility (ASQF) (see Figure 4.13).

[5]Corresponding to a 95% confidence bound of the bi-dimensional position error in the horizontal local plane for the worst user location

[6]Correspondoing to a 95% confidence bound of the uni-dimensional unsigned position error in the local vertical axis for the worst user location.

- *RIMS*

  The main function of the RIMS is to collect measurements from GPS satellites and to transmit these raw data each second to the Central Processing Facilities (CPF) of each MCC.

- *MCC*

  There are four MCC distributed around the EWAN. One of them is the main MCC and the mission of the other three are to support the main MCC in case of failure. The MCC is subdivided into the Central Control Facility (CCF) and the Central Processing Facility.

  - *CCF*

    These facilities are manned on a 24/7/365 basis in order to ensure permanent service monitoring and control.

  - *CPF*

    Provides EGNOS WAD corrections (clock corrections for each GPS satellite in view of the network of RIMS stations valid in all the broadcast area, ephemeris corrections to improve the accuracy of spacecraft orbital positions, model of ionospheric errors over the EGNOS service area in order to compensate for ionospheric disturbances on the navigation signals, estimation of the residual errors, etc.) and ensures the integrity of the EGNOS users.

- *NLES*

  The NLES receive the message elaborated by the CPF at the MCC in order to transmit it to the GEO satellites for broadcasting to users and to ensure the synchronisation with the GPS signal. There are two NLES for each GEO Satellite.

- *EWAN*

  EWAN is the network that links all the EGNOS components.

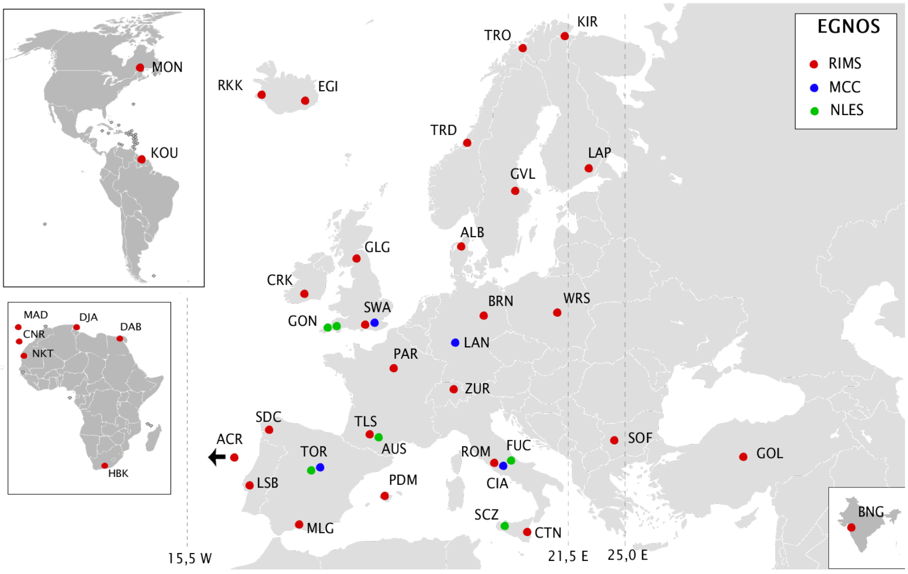


Figure 4.13: EGNOS Ground Segment distribution

Space Segment

The Space Segment is composed by three GEO Satellites whose mission is to broadcast the signals received by the NLES in order to provide the service in the whole service area of EGNOS (see Figure 4.14). The satellites broadcast the corrections and integrity information for GPS satellites in a right-hand circularly polarised (RHCP) signals in the L1 frequency band (1575,42 MHz). The broadcast signal is a combination of a 1023- bit PRN navigation code of the GPS family and a 250 bits per second navigation data message carrying the corrections and integrity data elaborated by the EGNOS ground segment. The level of the received RF signal at the output of a 3 dBi linearly polarized antenna is within the range of –161 dBW to –153 dBW for all antenna orientations orthogonal to the direction of propagation [15].

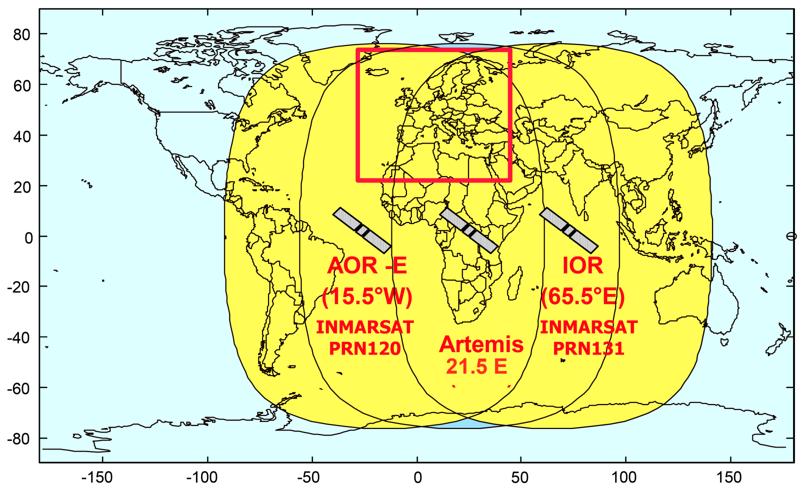


Figure 4.14: Geostationary satellite Broadcast Areas

User Segment

There is a wide range of EGNOS receivers available. There is a list of receivers made by Helios as part of a market study where the receivers are classified by the type of application the user demands. The receivers' list can be seen at [67].

4.2.2.2 Errors magnitude

As mentioned above, an EGNOS receiver can correct the main sources of error that affects the pseudorange. Table 4.2 shows the contribution of the errors using EGNOS and in a GPS Stand-alone situation. The error sources analysed are the Satellite Residual Error for the Worst User Location (SREW), the User Ionospheric Vertical Delay (UIVD), troposphere, receiver noise and multipath contributions as well as the final User Equivalent Range Error (UERE) [15]. The improvement in accuracy is clearly noticeable (see Figure 4.15).

Table 4.2: Errors magnitude in positioning

Error Sources (1σ)	**Error Size (m)**
GPS SREW	2.3
Ionosphere (UIVD error)	0.5
Troposphere (vertical)	0.1
GPS Receiver noise	0.5
GPS Multipath (45º elevation)	0.2
GPS UERE 5º elevation (after EGNOS corrections)	4.2
GPS UERE 90º elevation (after EGNOS corrections)	2.4

(a) Typical EGNOS SIS UERE

Error Sources (1σ)	**Error Size (m)**
GPS Clock and Ephemeris Errors	4.0
Ionosphere vertical error	2.0 to 5.0
Troposphere (vertical)	0.1
GPS Receiver noise	0.5
GPS Multipath (45º elevation)	0.2
GPS UERE 5º elevation (GPS Stand-alone)	7.4 to 15.6
GPS UERE 90º elevation (GPS Stand-alone)	4.5 to 6.4

(b) Typical GPS Stand Alone SIS EURE

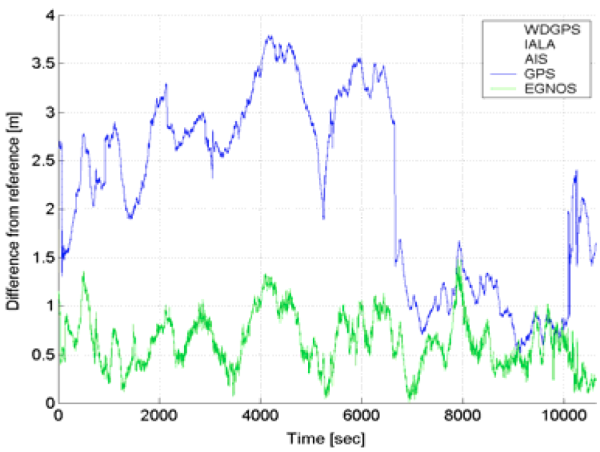


Figure 4.15: Kinematic maritime test near Lisbon comparing GPS without and with EGNOS [18]

4.2.3 Other SBAS

Apart from WAAS and EGNOS, there are another SBAS implemented by other regions. The principle of working is very similar to the systems previously explained, hence only the main characteristics of each will be described in this section.

4.2.3.1 System of Differential Correction and Monitoring (SDCM)

SDCM is the System of Differential Correction and Monitoring [19], the augmentation system developed by the Russian Federation to improve the GPS/GLONASS accuracy in the Russian territory. The system was put into operational testing in 2007. Figure 4.16 shows the first distribution of the reference stations network.

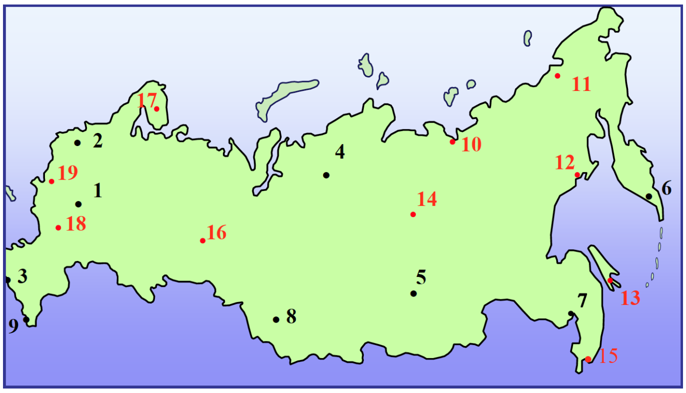


Figure 4.16: SDCM Reference Stations distribution [19]

4.2.3.2 Multi-functional Satellite Augmentation System (MSAS)

Multi-functional Satellite Augmentation System (MSAS) [68] is the SBAS developed by Japan to improve the availability, accuracy and integrity of GPS in the east of Asia (mainly in Japan). The system has two GEO satellites called MTSAT-1R and MTSAT-2, broadcasting in the L1 band (1575.42 MHz), at 500 bps and with a band-width of 2.2 MHz. The minimum signal strength on the earth surface is -161 dBw. In the future, it is planned to broadcast also in the L5 band.

The system has been developed to assure the non-precision approach. The observable horizontal accuracy (95%) is less than 2.2 m (the requirements states less than 220 m), the integrity is also under the non-precision approach requirement as well as the availability, which is over the 99,9% of the time. With this, the system can be used for En-route through Non Precision Approach phase of flight [68].

The MSAS Architecture follows the same kind of architecture of the rest of SBASs as shows Figure 4.17.

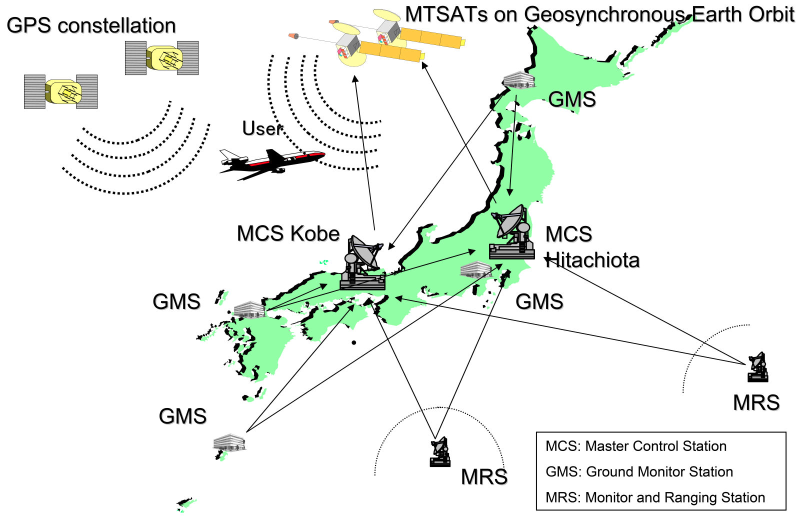


Figure 4.17: MSAS Architecture

4.2.3.3 GPS Aided Geo Augmented Navigation (GAGAN)

The GPS Aided Geo Augmented Navigation or GPS and Geo Augmented Navigation (GAGAN) [69] is the SBAS using GPS/GLONASS developed by the Indian government. Although the system was designed for civil aviation, a wide range of applications favoured by GAGAN.

GAGAN has been implemented in three phases, the *Technology Demonstration System* (TDS), the *Initial Experimental Phase* (IEP) and the *Final Operational Phase* (FOP). The first phase is the first step for the full operation of the system and it mainly consisted in the implantation of the Reference Stations[7], the Master Control centre[8], an Indian Land Up Link Station[9], the Navigation Transporter (with L1 and L5 functionality) and the network to link all the elements. The idea was to make the necessary tests in a small region of India. When finished, the second phase main objective was to extend the coverage to all the air space of India. When the third phase will be finished, the system will be fully operational.

One of the main highlights of this system is that, due to the proximity of the region to the equator[10], the estimation of the Ionospheric delay over the coverage area will be more

[7]The eight Reference Stations during the TDS phase where stablished at Delhi, Bangalore, Ahmedabad, Calcutta, Jammu, Port Blair, Guwahati and Trivandrum.

[8]The Master Control Centre is stablished at Kundalahari, Bangalore.

[9]Located in the Master Control Centre

[10]Note that the GEOs Satellites orbits directly above the Earth's equator (0º latitude)

accurate than in the rest of the SBAS [69].

Figure 4.18 shows the GAGAN architecture.

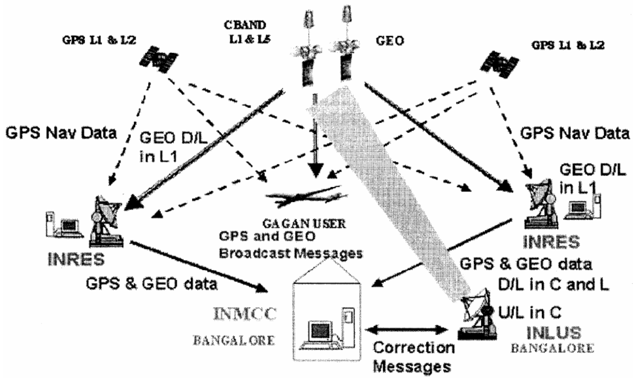


Figure 4.18: GAGAN Architecture

4.3 Assisted GPS (AGPS)

Assisted GPS (AGPS) [70] is an assisted system based on upgrade the standard GPS by providing the receiver with assistance data. Assistance for satellite positioning means provision of positioning related information in support of standard satellite positioning (correct GPS time, satellite ephemeris, etc.). Accordingly, assisting systems are those who provide support for standard positioning. Location Based Services (LBS) are becoming more and more popular to the point that the vast majority of mobile phones count with a GPS receiver. This new kind of GPS users are very different than the users who need a very accurate positioning or navigation like in aviation, marine or geodesic applications. For the users with a mobile phone GPS-integrated is useless to have to wait 12.5 minutes to receive the whole almanac[11] in order to estimate the position, because probably by that time the positioning necessity is over. Also, in many cases, this users need to receive the GPS signal in urban areas where the multipath error can be critical, or in adverse atmosphere conditions. Due to all this facts, the receiver can not be able to detect the low power GPS signal, or the signal can not be continuous to get all the almanac. So that, AGPS was designed to overcome these adversities.

The main reasons why AGPS was designed for are:

[11] When the receiver is in cold start, without any information about the status of the GPS constellation.

- The need of receive satellites signals continuously and there is not intermittence when ephemeris data is received in the period of time. Otherwise it is impossible to achieve positioning.
- Time To First Fix (TTFF) is long that it has 2 to 3 minutes for the best and most rapid receiver and the longest positioning time arrive to 12.5 minutes.

AGPS receivers are able to get information by a network that helps them to estimate the position. The assistance data that can be provided for the GPS receiver is:

- Satellite clock parameters
- Approximate location
- Ephemeris information
- Almanac
- Precise time

The AGPS basic elements are (see Figure 4.19):

- GPS Network (satellites, signal, etc.)
- Cellular network (to broadcast the assistance data)
- Location server (to provide the assistance data and the calculations)
- GPS (with GPRS, UMTS, etc. connection)

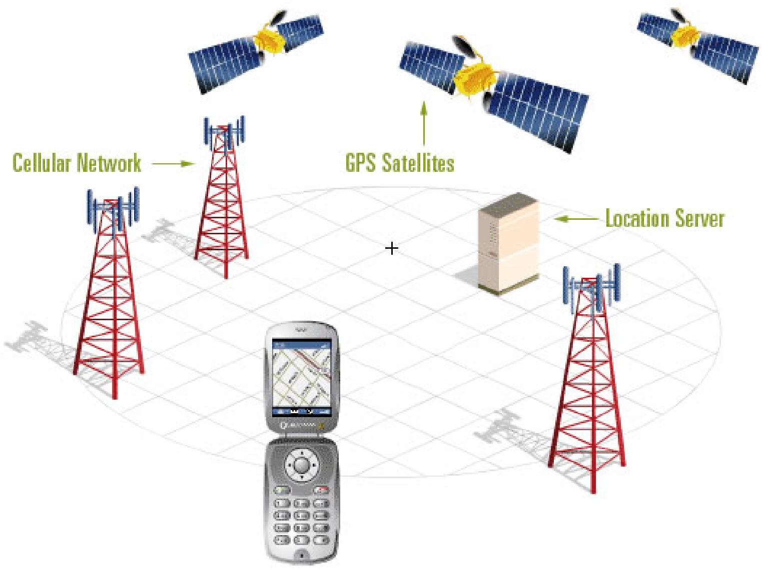


Figure 4.19: AGPS Architecture

Two different services are offered in AGPS, depending if the receiver (rover) calculates the position or if the position is calculated by an external server located in the network of the rover with a precise location known [70].

- *User equipment based mode for LBS*

  In this mode, the position calculation is performed on the rover using the data received by the provider. In this case the calculation is faster than without assistance data, due to the rate speed of the almanac information. The network can also provide precise time as well as local ionospheric conditions and other conditions affecting the GPS signal, enabling more precise calculation of position (similar to the DGPS principle, see page 58).

- *User equipment assisted mode for LBS*

  When the rover is not able to calculate its position due to the poor quality of the signal, an external server can calculate the position based on the information from the rover and the good satellite signal received. In other cases, the rover is not able to calculate the position, not because of the poor signal, but due to the lack of computation power. the positioning acquisition process by the server in the assisted mode is explained in [20], but the main idea is shown in Figure 83. Where t_{tr} is the pseudorange distance from the satellites to the rover, t_b is the pseudorange distance from the satellites to the base station. The server (base station) calculates the (X_0, Y_0, Z_0) coordinates using the Gauss-Newton method (like the normal GPS receivers) then, using the information about the relative position of the rover, the (X, Y, Z) coordinates calculated and transmitted to the rover.

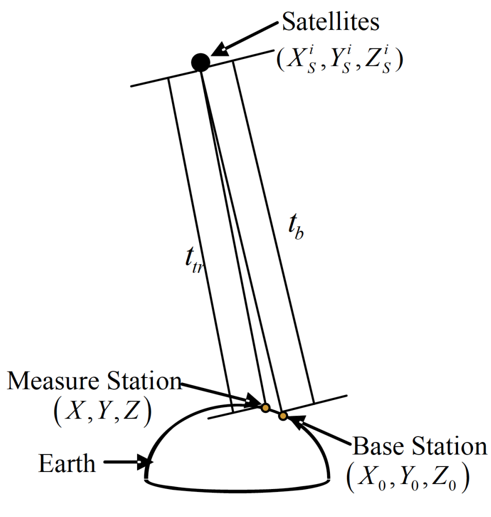


Figure 4.20: Principle of pseudorange calculating [20]

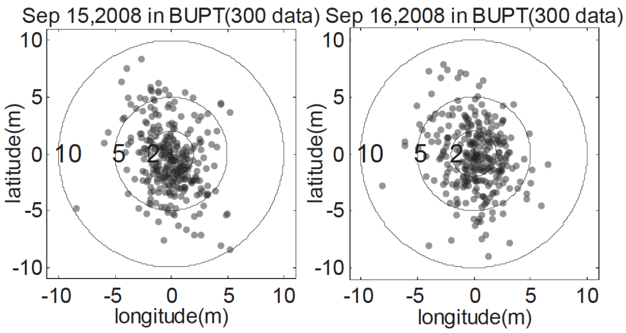


Figure 4.21: Distribution of positioning solution [20]

According to the survey carried out in [20], the distribution of the positioning of the rover using AGPS indicated that the biggest bias was less than 10 meters (see Figure 84). The mean positioning biases are about 3 meters, which is a good accuracy solution. About the time needed to calculate the position, mainly depends on the GPRS network, with a result of 3.21s in average and 5s at most, which compared to the traditional positioning method which need at least 2 to 3 minutes in TTFF (in the best case), the positioning method with AGPS has a greater advantage.

4.4 Conclusions

It is impossible to determine which of the techniques described is the best, due to the fact they are better or worse depending in the application of the user. About DGPS, the main problem is the initial and maintenance cost of the technology. The base stations are very expensive and the coverage area is not too big as well. Nevertheless, the accuracy achieved with this method is the best that a receiver can have, and can be even higher if it is combined with another technique.

Regarding the SBAS techniques, are very useful to have high accuracy in areas not covered by a DGPS base station. The WAAS system is widely used by the aviation community, although civil users can also use it. The problem of this system is that it only has coverage in the United States. For the European users, the best SBAS option is to use the EGNOS system. About the accuracy provided by these systems, thanks to the ionospheric model the user can correct almost completely the ionospheric error, one of the most important errors in GPS.

By last, AGPS is the most widely used technique by the users that do not need a very high accuracy, but a very good signal reception at any time. The combination of a GPS receiver and a transmission module to receive the assistance is more and more common in mobile devices, providing the user with the possibility of receiving the assistance broadcasted by the mobile network operator. In case the user would need more accuracy in positioning, this technique is not useful because its main achievement is to reduce the TTFF and to provide an approximate positioning in areas with poor signal power.

Part III

Tracking Systems

Chapter 5

Tracking Systems

5.1 Passive and active tracking systems

This chapter is divided into two different sections. The first one is an introduction to the active and passive tracking systems and their applications. On the second section, the reader can find the description of some different types of products used in the applications described previously.

5.1.1 Tracking systems overview

This part will be focused on tracking systems, mainly describing the principles of working for vehicle monitoring. The term tracking refers to the observation of people or objects in motion to supply their respective position in a sequence timely ordered. This data can be used subsequently (or simultaneously) for multiple applications, for instance, to be represented on a map.

There are several types of tracking systems depending on the technology used (GPS, Radio beacons, 2G, 2.5G...), the type of service used (real-time, near real-time...), the final application, etc. The most commons, and the main purpose of this survey, are the systems that calculate the relative location of the target using GPS. Thus, that information can be stored in a flash memory (or equivalent) or simultaneously transmitted to a remote server by GSM Network.

About the GPS tracking systems, there are two categories depending on which method is used to get the information from the GPS receiver to the final application. If the information is transmitted in real-time (or near real-time) by GPRS, SMS, CSD or other mean to the remote server, the device is called *active*. On the other hand, a *passive* device is the one that stores all the location data in an internal memory and afterward dumps it to the database.

Although the architecture of each device or system is different, we can identify a number of common parts in all. Figure 5.1 shows both active and passive architectures diagrams.

(a) Active architecture diagram

(b) Passive architecture diagram

Figure 5.1: Active and passive architecture diagrams

With regard to active systems, the main components of the device are:

- Positioning Module (GPS)
- Transmission Module (GSM/GPRS)
- I/O Interfaces

There could be many variations, such as a memory that can be used when the GSM/GPRS network is not available to transmit the data, or when the uses configures the device to work in a passive mode. Passive devices are all equipped with a memory (usually flash) to save all the parameters needed and do not have the GSM/GPRS Module. As mentioned before, many other features can be introduced to the devices, but this will be discussed in Section 5.2.

The database and the server are another very significant parts of the tracking system. Depending on the application needed, some parts can be omitted, but as this part of the Thesis is focused in vehicle tracking applications, will be considered as part of the system. Now, the most significant elements of tracking system are described.

Positioning Module (GPS)

The basic function of this module is to calculate the relative location of the object at any time. Mostly, this part also gives information about the time, speed, altitude, etc. so the tracking can be more complete.

Depending on the sophistication of the device, the GPS module can also have some augmentation system to improve the accuracy in positioning. The most common is A-GPS, due to the problems in positioning the vehicles inside the cities because of the multipath error produced by the buildings. Another reason of using this system is that, in the active systems, a GSM antenna is added to the device to send the positioning information to the remote server, so during the time the antenna is not being used, the assisted data can be received [71].

There are devices designed with SBAS for a major accuracy as well. These kind of devices are mostly used when the tracking needs to be very precise (i.e. to calculate the coordinates of a road with a technical purpose).

In order to avoid the loss of data in GPS black zones, some gadgets are implemented with an Inertial Navigation System (INS). This system is used to calculate the position of the object by a computer, motion sensors, and gyroscopes. With these elements and knowing the exact position in the time the GPS signal is poor, the system can easily calculate the position via dead reckoning. By the time the GPS signal stills undetectable, the tracking device can send or store the data. The accuracy of the INS is worse than the GPS, and the more time the INS is being used, the more error the measure contains.

Transmission Module (GSM/GPRS)

This part is only common in the active tracking devices. In fact, the transmitter module can be done by any other technology such as RF, satellite communication, Wi-Fi, etc. but in the area this part is focused the devices mainly use the GSM/GPRS bands.

This module is in charge of the transmission of the parameters gathered by the GPS module in order to be sent to the remote server. Two types of technology have been mainly used in the design of the tracking gadgets, data sending by SMS (Short Message Service) or by GPRS (General Packet Radio Service). The first method used was by SMS due to the large coverage of GSM all over the world, but several problems appeared. First of all, in one SMS there is only space for 160 characters of 7 bits (140 characters of 8 bits), as a consequence, the update of long data to the server is very expensive. There is no guarantee of the deliver time and also the time delay of the transmission is a bottleneck for real-time applications. The bit-rate of SMS is 9,6 kbps.

The General Packet Radio Service is an enhancement of GSM networks to support packet switched data services (See Figure 5.2). This technology provides data rate of 56-114 kbps and the transmitter knows at any time whether the server is receiving the data or not. GPRS operates on the existing GSM network infrastructure that it utilizes available time slots during each frame transmission. Thus, it does not overload the existing GSM network traffic and can efficiently provide data services. As a consequence, the price for sending big quantities of data is cheaper than in SMS. The main problem of the devices that uses this technology is that the coverage is smaller than the GSM 2G (SMS) coverage. As a result, the majority of the devices can switch from one mean to the other depending on the quality of the signal, ensuring that the data is sent to the server at all times [72, 73].

When the device is located in an area without GSM coverage, the GPS Module sends the data to an internal or external memory which backups the data to be further transmitted, when the device detects GSM signal [74].

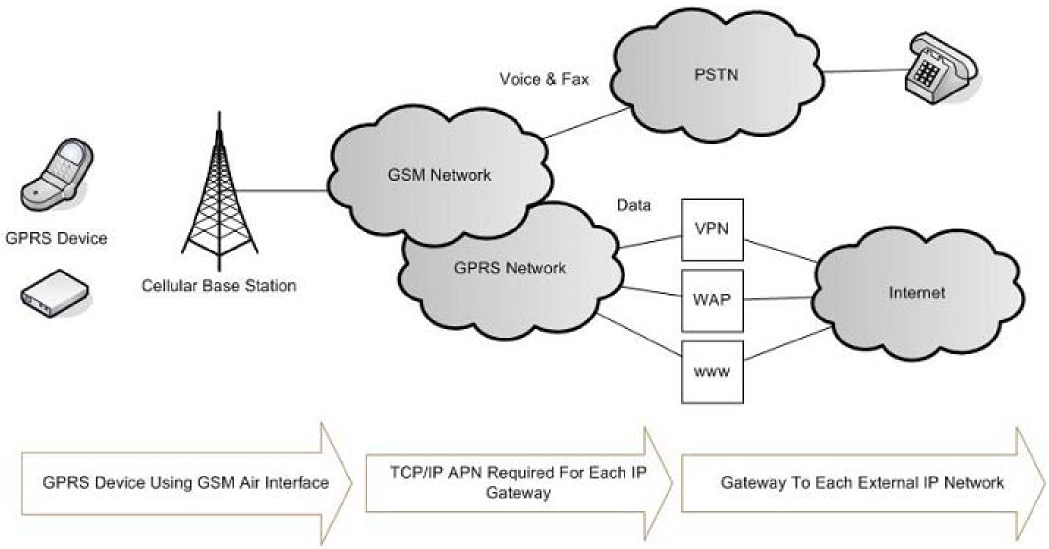


Figure 5.2: GPRS Architecture

I/O Interfaces

All the devices have some I/O interfaces to permit the manipulation of the stored data and to configure the device. Many of the gadgets do not have any screen or buttons to configure it, so a connection to a computer is needed. In the case of the passive tracking devices, the I/O interface will be the only way to get the saved data. Several types of interfaces can be implemented in a gadget such as serial port RS-232, Ethernet, USB, etc.

In addition, I/O interfaces can be used to monitor the status of some parts of the vehicle (wheels pressure, fuel, engine problems, electronic problems, gas detection, etc.) or get information about the environment (temperature, humidity, air pressure, etc.) that can be useful for some applications, i.e. in real-time monitoring of dangerous goods transport [75].

Database and remote server

This part of the system is clearly separated from the tracking device and is responsible for processing the information transmitted by the GSM/GPRS module. Firstly, the data reaches the database, where they are stored for later use. The most common application is to print the vehicles' path or position on a map (GIS). The application will be responsible of obtaining the data from the database to process it and finally represent it on the map [76].

In cases in which communication between devices is via GPRS, the device will have its own IP, so that communication will be much faster than if done via SMS. With GPRS Network communication, real-time applications are possible.

Regarding the database can be implemented using any database management system such as DB2, PostgreSQL, Oracle or MySQL. As well as the server can be configured with any web server software in case of the data has to be displayed in Internet. In cases the data is not needed to be in a server, this element can be omitted.

Figure 5.3 shows an example of active tracking system architecture with the elements described above.

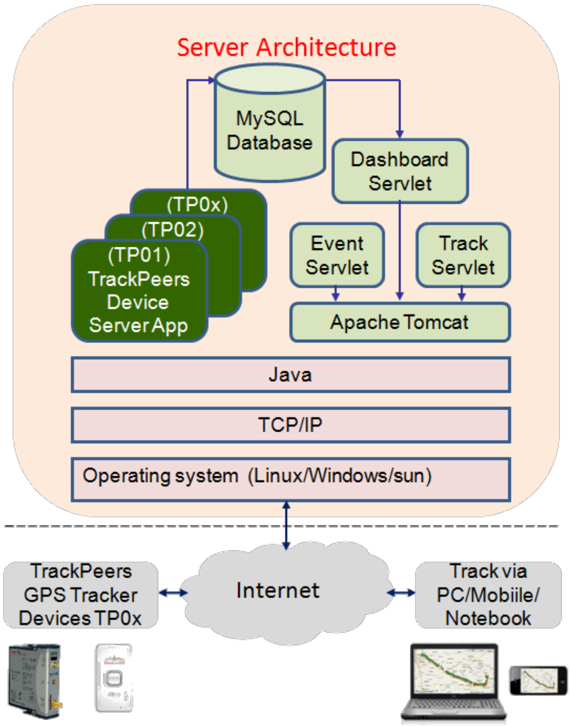


Figure 5.3: Example of active tracking system architecture

5.1.2 Tracking systems applications

There are several different applications related with tracking systems, not only for vehicle tracking but also for people tracking (i.e. for offenders or people who are not allow to leave a specific area or country). In this section, only vehicle tracking applications will be described. Four different types of tracking can be distinguish:

- Fleet management
- Urban transit management
- Monitoring driving behaviour
- Stolen vehicle recovering

Although the main idea of all of this applications is to get the vehicles' path at any time, many different variances can be considered in each type.

Fleet management

For many companies, being able to track all their vehicles in real time has a significant value. In transport companies, tracking systems allow them to have precise control of the place where each package is. Consequently, they can offer the clients an added value to the product, as the client would be able to consult the exact point where the package is and the estimated time delivery.

In the case of private ambulances companies, efficient service can be ensured when sending a vehicle to a particular area. Knowing the exact location of each ambulance makes easy to notify the nearest.

With regard to carriers of dangerous goods, this technology provides a large increase in security. As explained above, there are gadgets that monitor external and internal parameters to the vehicle, so that by the time the sensor detects any abnormality, a signal is sent to the server. With this, the server can act consequently on warning the driver or even controlling somewhere the vehicle remotely [75].

Urban transit management

In this category are included monitoring schedule adherence of buses applications, making easy to check the level of success of the service and more comfortable for the user as he is always inform about the incidences. Some cities have developed a system in which the time left for the next bus/tram/train is showed in a screen or even transmitted, via Bluetooth or SMS, to the passengers.

Another widely used application in many cities is to remotely trigger changes of buses' signs, such as the name of the next stop in the screen or the change of direction when the bus reaches the end of the line. As the track is being processed in real-time, it is easy to remotely control the dynamic parts of the bus in order to not disturb the driver.

Monitoring driver behaviour

These types of application are not as usual as the other two described above, although are more and more used nowadays than time ago. These applications monitor the location, time, speed, etc. of the vehicle in order to inform a third person. The relationship between the driver and the third person is usually employer/employee or parents/teen. The main purpose of this is to know at every time if any irregularities are being committed, such as exceeding the speed limit or to avoid the use of firms' vehicles for personal purposes.

Stolen vehicle recovering

This application is based on the incorporation of a tracking device in the vehicle, properly disguised, to know the position of the vehicle in case of theft. Depending on the sophistication of the product, some parts of the vehicle can be controlled remotely, i.e. activate the car alarm, stop the engine or disconnect all the electronic parts preventing the use of the vehicle.

With the advent of this technology, many insurance companies have lowered prices to customers who incorporate a tracking system, as the odds of loss of vehicle theft decrease significantly.

5.2 Products

5.2.1 Active and passive products

As mentioned in page 87, there are two different types of tracking products according to the method used in the transmission of data. In this section some products will be presented to provide the reader a global idea about the actual products in the market and their characteristics. The range of products is very wide depending on the features of the devices, for that, only a selection of the most remarkable gadgets is going to be examined. Due to the amount of possibilities the active products have in respect with the passive, this part will be more focused in active products.

5.2.1.1 Passive products

Passive products are the devices that do not send the location data to the server while is being gathered, but afterwards. The best advantage of these products is the fact the owner does not have to pay monthly fees because all the data is transmitted directly from the device to the computer. In cases the device is designed to support SBAS or A-GPS (which is not common in these kind of devices), the owner will have to pay the according fees of the augmentation system in use. The most common augmentation system in a passive device is SBAS due to the fact is not needed another antenna in the range of, for example, GSM to receive the augmentation information (like in A-GPS). In case the device is designed with A-GPS, the data receiver module can be used to transmit the navigation data to a server via GSM, so the device becomes active.

There are several ways to store the data depending the manufacturer. However, the most widely used is the NMEA protocol. Devices implemented with the NMEA protocol make sure the compatibility with many other devices and software [77]. In the end, the software must easily interpret all the data gathered by the gadget in order to make the information comprehensive for the end user. An example about how the NMEA data is stored is given in [78].

In passive products the accuracy of the data is not as important as in the active devices. Normally active products with high accuracy are used to send messages to the vehicle when it is arriving to some position, but this is not the case of the passive products. Due to that fact, these devices are not going to be deeply examined, as it is not strictly related with the main objective of the Thesis. Nevertheless two different devices will be described; the first one is standard; the second is equipped with SBAS support.

The standard device chosen is the *GPS Tracking Key Pro* developed by *LandAirSea,* the more sophisticated is the *GT-750F(L)-Lite* developed by *CanMore Electronics Company* [78]. Two features have been the most significant to select this last device among the other competitors, firstly the fact that SBAS is supported, and secondly that the NMEA protocol is used.

GPS Tracking Key Pro

This device is one of the best for a non-accurate tracking, such as stolen vehicle recovery or monitor driver behaviour. This model has been designed to be placed anywhere in the car, either inside or outside the car. The gadget is provided with a powerful magnet and is water resistant, so there is no problem to install it under the vehicle.

The *GPS Tracking Key Pro* (see Figure 5.4) records every second the speed, location of stops, duration of stops, time en route, arrival addresses and direction of vehicle within 2.5 meters of accuracy. The principle of working, as mentioned before, is to calculate the position and the rest of parameters using the L1 C/A Code and store all the data every second in a non-volatile flash memory in NMEA format. The capacity of the flash memory is about 100 hours of driving. The device uses 2 AA batteries, which provides a two-week battery life driving 4 hours per day, although it can be plugged to the vehicle's main power supply.

Figure 5.4: *GPS Tracking Key Pro*

About the GPS receptor, it provides SPS accuracy, with up to 2.5 meters of accuracy. The acquisition time for a cold start is 39 seconds, while in hot start is less than 2.5 seconds. Once the GPS receiver calculates and the microprocessor stores the data, this can be dumped to the computer using a USB port. With this, the user can check the information on *Google Earth*, a graphic interface where the routes are printed over the global map.

The dimensions of this device are 76.5 mm lenght, 49.5 mm width and 35.5 mm heigth. The price of the *GPS Tracking Key Pro* is about 120 €.

GT-750F(L)-Lite

GT-750F(L)-Lite (see Figure 5.5) is a passive tracking device whose best feature is the possibility to use the SBAS mode if the device is inside the coverage area of the service. The SBAS service has fees, but the user does not have to pay monthly fees for the transmission of the data, as it is transmitted afterwards via USB to the computer. Without using the SBAS, the horizontal accuracy achieved is 5 m in positioning and 0.1 m/s in velocity. If the SBAS option is used (with WAAS or EGNOS, see Section 4.2) the accuracy can be reduced up to 2-3 meters.

One of the most critical parameters in a passive tracking device is the acquisition time, owning to the fact that the object is usually a car (urban areas, woods, etc.) and the device does not count with AGPS. However, the manufacturer fixes the maximum start-up time in 1 second in the case of hot start, and 30s for a cold start. Regarding the sensitivity[1], the minimal signal power needed for the acquisition process is -147 dBm, whereas in tracking is -160 dBm. In page 20 the power design for the GPS signals are described, and C/A signal (the signal which receives the device) is designed to be at minimum -158.5 dBm in the earth surface. With this, could be said that the specifications of sensitivity are within a good parameters.

[1]Sensitivity is the minimum magnitude of input signal required by a device to carry out a particular function.

Figure 5.5: *GT-750F(L)-Lite*

About the stored data, the device has a memory flash of 2MB, which is equivalent to 256k records (record data is 16 Bytes in NMEA format). With this amount of memory, taking into account the vehicle is being tracked 4 hours every day, there is enough space for more than 88 days of tracking without dump the data to the computer. However, the batteries of the device only allow less than 20 hours of function. In that case, only by plug a replacement or a charger adapter the data can be stored without problems. The data stored is compatible with some mapping software to check the route of the vehicle and all its parameters (location, speed, time, tags, etc.) in a map, such as Google Earth, TrackMaker or LOGG extension.

The dimensions of this device are 73 mm lenght, 44 mm width and 21 mm heigth, and the price is around 50 €.

5.2.1.2 Active products

Regarding the active products, the most significant feature is the large amount of applications that can be implemented. Thanks to the fact that the data is transmitted from the device to a remote server, the data can be easily manipulated from any location. The active products offer is wider than the passives; consequently there are many differences between the low cost products and the more expensive ones.

The less sophisticated devices are implemented with a single frequency GPS receiver, with an accuracy of 15 m (without S/A) and the transmitter module is usually a GSM Module that sends the data via SMS. Nowadays, the standard tracking devices are implemented with GPRS technology. GPRS technology enables a faster transmission of the data to the remote server as well a direct connection with it (in SMS the transmitter does not know whether the message is received or not). In addition, the technology used in the transmitter module can be based in the 3rd generation of standard in mobile phones

(HSPA, which is included in the 3G+ standard). Also in terms of GPS receivers there are several levels of sophistication, from the single frequency device to the dual frequency with augmentation systems such as SBAS, AGPS or DGPS. Apart from that, some devices are designed with INS for a more accurate positioning when poor satellite signal.

In order to give the reader a global idea about which kind of active products are in market and their possibilities, three different devices and one significant application are going to be described. Each of the three devices is in one grade of sophistication. According to that, the products are described from the simplest to the highest developed.

Airlink PinPoint XT

The *Airlink PinPoint XT* (see Figure 5.6) is the real-time tracker developed by *Sierra Wireless* designed to provide Automatic Vehicle Location (AVL) and Mobile Resource Management (MRM). Between its applications, the most significant are fleet management, asset tracking and vehicle telemetry. *Sierra Wireless* is a company specialised in M2M (Machine-to-Machine) communications in mobile scenarios. This product is one of the most convincing active trackers amongst its competitors.

For a robust M2M communication, the gadget is powered by ALEOS technology, the embedded core technology of the *Sierra Wireless* that provides persistent connectivity, end-to-end security, real-time two-way data exchange, and remote device management. Thanks to that, there is no need for the user to worry about real-time GPS reporting or GPS store and forward.

The device is also implemented with several I/O interfaces that, with the AirLink suite of management tools, enable remote configuration, administration, and control of deployments of any size, from one device to thousands. This characteristic is very significant for fleet management, given that the control centre of the company can check all the I/O interfaces of the different vehicles. There are 6 programmable I/Os and 3 Analog/Digital.

Regarding the GPS, there is no particularities in this technology since it is implemented with a single frequency GPS receiver. The accuracy is the typical SPS accuracy (less than 3 meters 50% CEP[2]), with a TTFF of 39 seconds. The *Airlink PinPoint XT* is also provided by a GPS SMA connector in order to use an external antenna for a better signal reception. This device is not designed with any augmentation system because the main purpose of its applications is not the accuracy in positioning the vehicle. In fact, its main goal is the use of the I/O interfaces provided such as odometer, engine problems sensors, gas sensors (for a dangerous goods trucks), etc. to report the status of them, as well as the location, to the control centre.

[2]CEP (Circular Error Probable): Values stated as CEP apply to horizontal accuracy only. Half of the data points fall within a circle of this radius centreed on truth, half lie outside this circle.

Figure 5.6: *Airlink PinPoint XT*

Concerning the transmission module, the device is better equipped than many other active systems. The need of the transmission of the data gathered by the sensors and the GPS in real-time is the reason of the technology chosen in its design. The device is compatible with GSM network (which nowadays has the wider coverage in mobile communications) and the transmission is made by GPRS. The device can also use the EV-DO technology, implemented with CDMA, which maximizes the quantity of data in transmission providing higher bit-rates than GPRS. The problem is that the coverage is not as wide as GPRS, so in the areas out of 3G coverage, the device switches the transmission method to 2G, if possible. In terms of bit-rate, EV-DO Rev. A offers a forward link rate up to 3.1 Mbps and a reverse link rate up to 1.8 Mbps, rates really higher than in GPRS. Like with the GPS Module, the transmission module has been designed with a SMA RF connector to provide better signal reception and, of course, there is a SIM Card slot to enable the communication with the service provider. As mentioned above, in case of being in a non-coverage without possibility of sending the information required, the *Airlink PinPoint XT* is able to store more than 3000 messages and forward them when the connection is available.

Depending on the services contracted when buying the device, the price can be lower or higher. Notice that active devices normally have monthly fees in order to use a remote server or a software to manage the tracks, as well as the data transmission costs. For that, some telecommunications providers offers some discounts for the device in case the client contracts some specified services. The dimensions of this device are 76 mm lenght, 27 mm width and 121 mm heigth, and the price is around 400 €.

Blackberry Bold 9000

Mobile phones implemented with a GPS Module are becoming more and more popular lastly. Several trades are in market providing this technology such as Blackberry, iPhone or HTC. Almost all these kind of devices are implemented with a GPS Module with AGPS, so the TTFF and the accuracy in positioning can be improved using the data received by the Transmission Module. To give an example to the reader, the device described is the *Blackberry Bold 9000* (see Figure 5.7), a mobile phone full of applications of different types.

Figure 5.7: *Blackberry Bold 9000*

The best feature of that device is the AGPS augmentation system and the benefits that it provides. With AGPS, the acquisition time of the signals decreases significantly, which makes the batteries life longer, as well as improves the accuracy in positioning. The majority of the users of that devices are citizens which use the gadgets inside the city, consequently the multipath error is very high and the accuracy on positioning can be up to tens of meters. In addition, common user routes are short, so there is no point to wait for some minutes to get the location. With this, the hybrid GPS+Mobile Phone represents a great step forward. In order to avoid service fees for the AGPS, there is an option to turn off the assistance in case it is not necessary.

Regarding the transmission technology, *Blackberry Bold 9000* is compatible with GMS, UMTS and CDMA Networks. Consequently, there is the possibility of real-time tracking services. The mobile phone does not have previously installed the application to do remote tracking (transmit the position to a server). However, there are several applications that work on background and send the information periodically. This is very useful for transporters, due to the fact they can integrate in only one device the telephony and the tracking system. A part from the tracking system, the device also has some applications for navigation, very useful for the transporters as well.

In case the device is connected to a CDMA Network (i.e. in the U.S.A.), if the user makes an emergency call or the device is in Emergency Call-back Mode, an emergency operator might be able to use GPS technology to estimate the location.

Like in the previous device, depending on the services contracted to the telecommunications provider the price of the devices can vary significantly. However, the price without any service added is estimated around 350 €.

The dimensions of this device are 114 mm lenght, 66 mm width and 15 mm heigth.

AsteRxi

AsteRxi (see Figure 5.8) is the high-precision tracking device developed by Septentrio Satellite Navigational and is one of the most sophisticated active product in positioning and tracking [79]. The most significant feature is the high accuracy that can be achieved thanks to the multiple augmentation systems implemented and the dual frequency to receive both GPS and GLONASS signals. The receiver provides cm-level positioning as well as an extensive set of measurements (raw data, position velocity, acceleration, time). The device includes 136 hardware channels for simultaneous tracking of all visible satellites in GPS and GLONASS constellations, as well as up to 3 SBAS channels, with WAAS and EGNOS amongst them.

Figure 5.8: AsteRxi device

Another augmentation systems implemented in the device is the possibility of receiving DGPS with RTK, that is, a single reference station provides the real-time corrections. Regarding the positioning accuracy, depending on the coverage of the augmentation systems and the quality of the signal received can vary considerably. According to the manufacturer, the standalone accuracy is 1 m for horizontal and 1.6 m in vertical. With SBAS, the accuracy is better, with 0.5 m and 0.7 m in horizontal and vertical respectively. With DGPS, the horizontal accuracy is better than in SBAS (up to 0.4 m) but the vertical is worse (0.8 m). For higher accuracies, RTK must be enabled, in that case horizontal and vertical accuracies are 1 cm + 1ppm and 2 cm + 2ppm respectively. These last accuracies, are more than enough for the most of the applications described in Section 5.1.2.

Concerning the tracking system of the device, notice that the data is formatted using the NMEA protocol. Another remarkable feature is the possibility of adding an Inertial Measurement Unit (IMU), an external device composed by accelerometers and gyroscopes to provide velocity, orientation, and gravitational forces in areas where the signal is poor. This device can be also used to correct some errors in positioning, comparing the information from the IMU and the data gathered by the device.

The dimensions of this device are 60 mm x 90 mm for the integrated circuit and 58 mm x 58 mm x 22 mm for the IMU.

Real-time RaceFX

More than a device like in the other cases described above, this is an example an application only possible with the best accuracy in positioning. The main idea of this application is to monitor all the cars in Nascar races, which provide data about speed and position. The design of *RaceFX* had to overcome several adversities. Accurate vehicle positions needed to be obtained, calculated, and transmitted under conditions in which GPS satellite signals are frequently blocked or reflected. In addition, installing the GPS vehicle tracking system without affecting the aerodynamics of a car travelling 200 mph and yet maintaining good satellite visibility requires an innovative design supposed a non-trivial challenge.

RaceFX is composed by four subsystems: GPS, telemetry, time synchronization, and video overlay. Each racecar has a GPS receiver and a 900 MHz transceiver. *RaceFX* employs a sophisticated telemetry system that transfers position and other vehicle information from all race vehicles to a central processor at the rate of five times per second. DGPS, pseudorange and carrier phase tracking techniques generate vehicle coordinates accurate to 50 centimetres (1σ). The telemetry conveys differential messages from GPS base stations to the racecar rover units at 0.5 Hertz and racecar rover information to the video subsystem at 5 Hertz.

Six broadcast cameras are instrumented to measure their pan, tilt, zoom, and focus 30 times per second or once per video frame. *RaceFX* interpolates racecar position information to correspond with the camera orientation in each video frame. High-speed computers combine this data to appropriately juxtapose the car and data in the video frame.

The video overlay accepts information from all rovers and reformats it for individual video frames of the particular camera used in the broadcast. Racecars travel at speeds up to 90 meters/second. Relative timing between the video, and GPS must be accurate to one millisecond to keep time-induced errors below 10 centimetres. The GPS-based system maintains the timing to about 10 microseconds, or 100 times better than the minimum requirement. Racetracks must be accurate digitized for the correct working of the system.

Due to the speed of the cars and the buildings near the racetrack, satellites are constantly entering and exiting from the field vision of the GPS receiver. Consequently, there is a significant degradation on positioning. To overcome that problem, NovAtel and Sportvisionengineers developed several techniques to minimize these shadowing effects by incorporating a computerized model of the track into filters that provide more precise positioning. With this and the incorporation of a DGPS station in a visible place from all the track, racecars are able to calculate the exact position at every moment. Figure 5.9 shows a frame on TV of the *RaceFX* result.

Figure 5.9: *RaceFX* frame example [21]

As the reader can see, the final result is a real-time racecars monitoring with several parameters that can be checked at any time. This gives the television company a differentiation attribute amongst its competitors, impossible to achieve without the accuracy in positioning and the post processing techniques.

Chapter 6

Conclusions

This report is a theoretical description of the different positioning systems and the GPS Augmentation Systems. With the information that can be found in this Thesis the reader can get a global idea about positioning and navigation, how the systems work, advantages and disadvantages of them, history, new developments in each one, etc. The fact that all of the systems are characterised in the same document will help the reader the comparison between them, as all the significant features, principles of working and evolution are included. As the reader can see, the most significant systems described are GPS, GLONASS and Galileo due to the fact they are the most developed and popular nowadays (and in a short-term future).

About the *GPS Augmentation Systems*, the main purpose of this part was to give the reader the bases of the techniques to improve the accuracy in the GPS System. Most of them can be also applied to other system, since all the positioning system described are based in the same principles. In that part the reader can see how the accuracy is improved with each technique and the difficulty in implementing each one. With this, it was pretended to get the reader the necessary information to evaluate which is the best *Augmentation System* according to their necessities. In conclusion, about DGPS, the main problem is the initial and maintenance cost of the technology. The base stations are very expensive and the coverage area is not too big as well. Nevertheless, the accuracy achieved with this method is the best that a receiver can have, and can be even higher if it is combined with another technique.

Regarding the SBAS techniques, are very useful to have high accuracy in areas not covered by a DGPS base station. The WAAS system is widely used by the aviation community, although civil users can also use it. The problem of this system is that it only has coverage in the United States. For the European users, the best SBAS option is to use the EGNOS system. About the accuracy provided by these systems, thanks to the ionospheric model the user can correct almost completely the ionospheric error, one of the most important errors in GPS.

The combination of a GPS receiver and a transmission module to receive the assistance is more and more common in mobile devices, providing the user with the possibility of receiving the assistance broadcasted by the mobile network operator, which makes AGPS one of the most widely used *augmentation system*.

The last part of the Thesis is an introduction to the *Tracking Systems*. In that part, the main purpose is to show the reader the possibilities that the combination GPS + Augmentation Systems have. There is nothing clearer to achieve this than some practical examples, so in the last part the theoretical aspects are justified with examples and products available nowadays in the market. About the devices described, passive systems are more useful for those applications that do not need real-time monitoring, but further analyse of the track of the object. For real-time or near real-time applications, active devices are perfect. Depending on the price of the device and the technology used (use of *augmentation systems*, IMU's, transmission's module protocols, etc.) the product's possible applications will be wider. If the user is not looking for high accuracy to remotely track an object, the *Airlink PinPoint XT* or a *smartphone* with *tracking system software* would be enough. In case the user would need more accuracy in positioning to remotely control a vehicle, a product with similar characteristics to the *AsteRxi* would be a good option.

A future work on this area could be interesting if some products could be tested and compared in real conditions, not only in the theoretical conditions given by the manufacturers. Even though, the information given should is enough to give the reader a clear idea about the types of devices in the market and its applications.

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